Thesis/
Reports
Tabler,
R.D.

EVALUATION OF THE FIRST-YEAR PERFORMANCE OF THE INTERSTATE-80 SNOW FENCE SYSTEM

FINAL REPORT ON CONTRACT 16-247-CA

Prepared for the Wyoming Highway Department

by the

Forest Service, USDA

Rocky Mountain Forest and Range Experiment Station

Ronald D. Tabler, Principal Investigator

August 15, 1972

LIBRARY
DEC 4 · 1972
ROCKY MOUNTAIN S[illegible]ON

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
Rocky Mountain Forest & Range Experiment Station
240 West Prospect
Fort Collins, Colorado 80521

4040 (4300)
August 14, 1972

Mr. William G. Lucas
Superintendent and Chief Engineer
Wyoming Highway Department
P.O. Box 1708
Cheyenne, Wyoming 82001

Dear Mr. Lucas:

We are pleased to forward herewith three copies of our final report on "Evaluation of the First-Year Performance of the Interstate-80 Snow Fence System", as required under our cooperative agreement (Contract Number 16-247-CA) with the Wyoming Highway Department.

We have greatly appreciated this opportunity to participate with you in this important study, and look forward to continuing our cooperation in the future.

Sincerely,

KARL F. WENGER
Director

Enclosures

U. S. FOREST SERVICE

AD-83 Bookplate
(1-63)

NATIONAL

AGRICULTURAL

LIBRARY

LIBRARY COPY
ROCKY MT. FOREST & RANGE
EXPERIMENT STATION

Evaluation of the first-year performance of the Interstate-80 snow fence system

Final Report

on

Contract No. 16-247-CA

Prepared for the

Wyoming Highway Department

by the

Forest Service, USDA

Rocky Mountain Forest and Range Experiment Station

Ronald D. Tabler

Principal Investigator

August 15, 1972

ACKNOWLEDGMENT

I wish to express my personal appreciation to the Wyoming Highway Department for supporting the research reported herein. Particular recognition is due Messrs. William G. Lucas, Edward H. Crowe, and David J. Hanlin, for their part in making possible the timely application of our research results.

This report is respectfully dedicated to Mr. Robert L. Jairell, competent technician and faithful friend, without whom this study could not have been accomplished.

RONALD D. TABLER

TABLE OF CONTENTS

INTRODUCTION 1

THE PROBLEM 1

STUDY OBJECTIVES 5

APPROACH 6

Determination of R_m and q_s 6

Test of design precipitation equation 7

Determination of fence capacity and evaluation of fence performance 7

Evaluation of effects on visibility and ice formation 7

Fence efficiency as a function of snow accumulation 8

STUDY SITES, INSTRUMENTATION, AND MEASUREMENTS 9

RESULTS 18

General 18

Snow accumulation at Systems 1 and 23, and evaluation of methods used to estimate amounts of blowing snow 18

Analysis of drifting events 24

Evaluation of precipitation estimate 34

Performance of all fence systems 37

Capacity and general performance of the new standard-plan fence 45

Effects of fences on visibility and road surface conditions . .49

Fence efficiency 56

CONCLUSIONS AND RECOMMENDATIONS 56

LITERATURE CITED 61

APPENDIX 62

A. Instrument location maps 63

B. Snow accumulation data for intensive study sites 68

C. Residual snow upwind of the intensive study sites 70

D. Snow accumulation, mass transport, and weather conditions during drifting at the intensive study sites 71

E. Precipitation data 73

F. Water-equivalent storage data for all completed fence systems 80

G. Critique of existing fence systems, and recommendations for modifications to maximize performance 81

INTRODUCTION

The Wyoming Highway Department is presently installing snow control measures along the recently completed section of Interstate Highway 80 (I-80) between Laramie and Walcott. Blowing and drifting snow along portions of this new highway have proven to be exceptionally severe, and an acceptable degree of snow control can only be attained at considerable expense. In addition, there are unique technical problems associated with the blowing snow conditions on I-80 that require an innovative approach for solution. For these reasons, the Wyoming Highway Department has consulted with outside agencies and individuals in an effort to develop an effective and efficient snow control system. On January 27, 1971, the Forest Service, United States Department of Agriculture, Rocky Mountain Forest and Range Experiment Station, entered into a cooperative agreement with the Wyoming Highway Department. Under terms of that agreement[1], the Principal Investigator studied the blowing snow problem on I-80, and designed snow fence systems for the first-priority sites (those identified by Wyoming Highway Department personnel as requiring installation of snow control measures before the 1971-72 winter).

A $480,000 contract was let by the State in 1971 for installation of the control measures recommended in the final report to the Wyoming Highway Department (Tabler, 1971b). Because snow fences are also being considered for additional locations along I-80, and evaluation of the fences built in 1971 would permit improving the efficiency and economy of these future systems, the Wyoming Highway Department commissioned the Rocky Mountain Station to evaluate the first-year performance of the snow fences[2]. The results of that study are the subject of this report.

THE PROBLEM

The key to the success or failure of the I-80 snow fence system design is the method used to estimate the required storage capacity for each fence system. The general approach, as published by Tabler (1971a), assumes that the sublimation loss of transported snow is a linear function of transport distance:

$$\bar{q}_b = \bar{\theta}\,\bar{P}\,\bar{R}_c - (1/2)\bar{\theta}\,\bar{P}\,(\bar{R}_c^2 / \bar{R}_m) \quad \underline{3/} \qquad (1)$$

1/ Contract No. 16-225.

2/ Contract No. 16-247-CA (effective July 23, 1971).

3/ Bars over variables denote mean values. For example, $\bar{R}_m$ is the transport distance averaged over a specified period of time.

where $\bar{q}_b$ = mean annual amount of relocated snow arriving at a control site (ft^3 of water-equivalent per ft of width)

$\bar{\theta}$ = mean annual snow transfer coefficient, defined as the ratio between the snow relocated by the wind and that which falls as precipitation.

$\bar{P}$ = mean winter (November 1 - April 1) precipitation (ft)

$\bar{R}_c$ = mean (annual) distance upwind contributing blowing snow at a site (but never greater than $\bar{R}_m$), (ft).

$\bar{R}_m$ = the mean (annual) distance over which an average-size snow particle must travel before completely sublimating (evaporating), (ft).

The principal concepts and definitions embodied in Eq. (1) are shown diagrammatically in Figure 1.

In locations where there is ample wind to relocate all snowfall the snow transfer coefficient, θ, may be defined as

$$\theta = \frac{P - q_s}{P} \tag{2}$$

where q_s is the natural storage of snow behind vegetative and topographic traps over the distance R_c, and Eq. (1) can be written as

$$\bar{q}_b = (\bar{P} - \bar{q}_s)\ (\bar{R}_c - \bar{R}_c^2 \ / \ 2\bar{R}_m) \tag{3}$$

For the special case where there are no barriers to snow movement over the distance $\bar{R}_m$, $\bar{R}_c$ equals $\bar{R}_m$ and

$$\bar{q}_b = (1/2)R_m(\bar{P} - \bar{q}_s) = (1/2)\bar{\theta}\ \bar{P}\ \bar{R}_m \tag{4}$$

Equations (3) and (4), then, predict the average amount of blowing snow expected at a site over a winter. In the case of two or more rows of fence protecting a site, the total capacity of the system must also be sufficient to contain the relocated snowfall between barriers. Using the linear sublimation loss model (Eq. 1), the amount of blowing snow, q_f, contributed by the distance r between two rows of fencing is

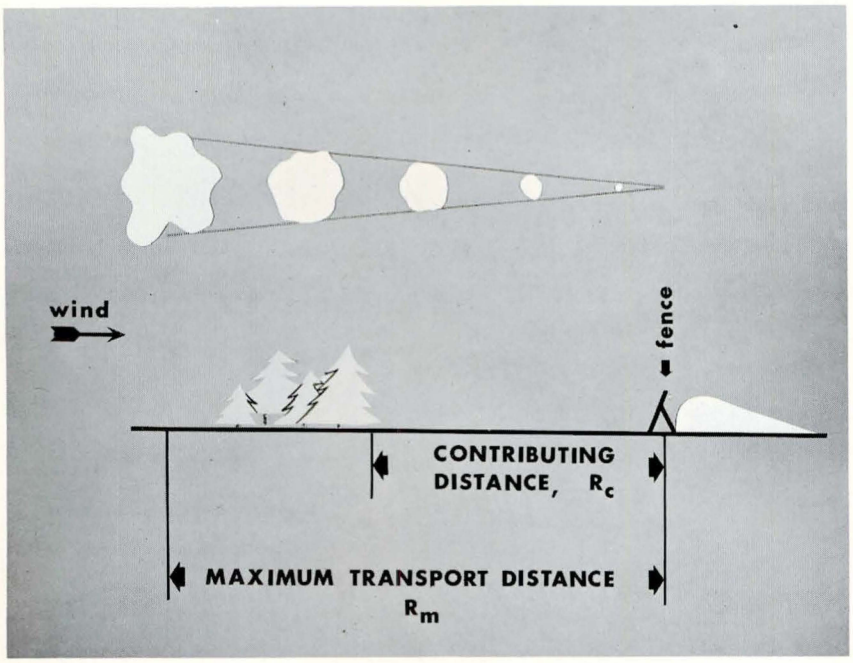


Figure 1. Diagram of the transport distance concept used to estimate the mean annual amount of blowing snow arriving at a control site. The transport distance, R_m, is defined as the mean distance over which an average sized snow particle (shown between the convergent dotted lines) must travel before completely sublimating. The contributing distance, R_c, is defined as that distance contributing blowing snow to a site, and may be equal to, or less than, R_m.

$$q_f = \theta P r - (1/2)\theta P (r^2/R_m) \quad (5)$$

Assuming that a fence system is 100% efficient in trapping all incoming snow over the season, the required average capacity, $\bar{q}_t$, of a system comprised of i rows of fences then becomes

$$\bar{q}_t = \bar{q}_b + \bar{q}_f = (1/2)\bar{\theta}\bar{P}\left[2\bar{R}_m - \frac{\bar{R}_c^2}{\bar{R}_m} + 2r_1 - \frac{r_1^2}{\bar{R}_m} + 2r_2 - \frac{r_2^2}{\bar{R}_m} + \ldots + 2r_i - \frac{r_i^2}{\bar{R}_m}\right] \quad (6)$$

Since the sum of the $\left(r_i^2/\bar{R}_m\right)$ terms is small compared to the other terms,

$$\bar{q}_t \doteq (1/2)\bar{\theta}\,\bar{P}\left[2\bar{R}_m - \frac{\bar{R}_c^2}{\bar{R}_m} + 2r_i + 2r_2 + \ldots + 2r_i\right] \quad (7)$$

In the original design of the snow fence systems on I-80, it was felt that the estimates for the factors in Eq. (3), and the storage capacity of the new standard-plan fence, were in themselves too uncertain to warrant the use of Eq. (7). Thus, Eqs. (3) and (4) were used to determine the amount of fencing required at each site.

A test during the 1969-70 winter showed Eq. (1) to provide a good estimate of the snow available to a single 12.5-ft-tall fence on Pole Mountain east of Laramie (Tabler, 1971a). However, to ensure maximum efficiency and economy of future fence systems along I-80, it was necessary to test and adjust the estimates of $\bar{P}$, $\bar{R}_m$, and q_s that were used in the design of the fence systems for the first-priority sites.

A second area deserving study is that of the performance of the new standard-plan fence developed by Wyoming Highway Department engineers; in particular, the true capacity of the 10- and 12-ft fences is unknown, since no studies have reported the performance of tall fences of this type.

It is also prudent to examine the performance of the various systems to determine their adequacy with respect to spacing, orientation, and topographic placement. Although the spacing criteria used for the first-priority systems are those generally advocated in the literature, the use of 10- and 12-ft-tall fences in tandem arrays is a new innovation, without published precedent. Also, proper fence orientation can only be achieved by a comprehensive study of prevailing wind directions during drifting events. The short period of time

available for such observations along I-80 during the 1970-71 winter may be responsible for orientation errors, despite the attempts to rationalize wind directions used in the initial design via a generalized model for surface winds. A winter's experience should ensure satisfactory orientation of future fences.

A final justification for studying the fence systems built in 1971 is to evaluate the potential for using snow fences to improve visibility and reduce ice formation on the road surface. No published information is available on this important aspect of snow fences.

STUDY OBJECTIVES

The general objective of this study was to evaluate the first-year performance of the snow fence systems installed in 1971 at the first-priority sites on I-80 between Laramie and Walcott Junction, Wyoming, and determine the efficacy of the method used to estimate the amount of relocated snow available at the control sites. For each site, the suitability of the system design (capacity, spacing, orientation, sequence of heights) was evaluated, and recommendations made for modifications in future fence systems.

Specific objectives were:

1. For two control sites (I.D. Numbers 1 and 23), test the values used to apply Eqs. (1) and (3) to the I-80 design:
   a. Determine the mean maximum distance of snow transport ($\overline{R}_m$) over the 1971-72 winter.
   b. Determine the snow transfer coefficient Θ, or the actual natural storage (q_s) upwind of the fence systems.
   c. Determine the actual precipitation along I-80 between Cooper Cove and Elk Mountain over the 1971-72 winter, and test the efficacy of the equation used to estimate the long-term mean winter precipitation ($\overline{P}$):

$$\overline{P} = 1.5 \text{ (Elk Mtn. Stn. Mean + 1.1)} \qquad (8)$$

   where the 1.5 factor corrects for wind effects at the (unshielded) Elk Mountain gage site, and the 1.1 is an elevation adjustment factor.
2. Determine the capacity of the new standard-plan snow fence used on I-80.
3. For all snow control systems constructed on I-80 in 1971:
   a. Determine if the 25H (H = total fence height) spacing factor is adequate for the fence heights used on I-80.
   b. Determine if fence orientation is approximately normal to the prevailing wind directions during the 1971-72 winter.

c. Determine the over-all adequacy of the control measures, including capacity and topographic placement.
d. Observe effects of the snow control systems on visibility and ice formation on the road surface.

4. Determine how the collection efficiency of a snow fence changes as the lee drift grows.

APPROACH

Objectives 1.a and b. (Determination of R_m and q_s): The two sites selected for this part of the study are at opposite ends of the problem stretch of highway, and appear to represent climatic, as well as geographic, extremes. In addition, these two sites also represent the extremes of conditions encountered for natural upwind snow storage--site #1 is characterized by short-grass vegetation and q_s should be quite small for most events. Site #23, by comparison, is typical of sites with sagebrush vegetation, which accounts for significant natural snow storage over the distance R_m. These two locations were therefore not selected to be replicates.

Because there are no significant upwind barriers to snow movement over the expected range of values for R_m at either site, Eq. (4) applies where

$$q_b = (1/2) R_m \left(P - q_s \right) = (1/2) \theta \, P \, R_m$$

It will be shown later in this report that the trapping efficiency of a sequential array of tall barriers spaced at 25H will remain above 90% until the fence farthest downwind contains about 20% of its maximum snow retention capacity. Over a short period of time (1 week), drift ablation would be negligible, and the amount of snow water-equivalent, v, accumulating behind the fence system can be assumed equal to the amount of relocated snow (Δq_b) arriving at the fence system over the time interval $\underline{i}$:

$$\left(\Delta v \right)_i \doteq \left(\Delta q_b \right)_i \qquad (9)$$

Substituting and solving Eq. (4) for $(R_m)_i$

$$(R_m)_i = 2(\Delta v)_i \; / \; (P - q_s)_i = 2(\Delta v)_i \; / \; \theta_i P_i \qquad (10)$$

For the entire season,

$$\bar{R}_m = \frac{\Sigma P_i (R_m)_i}{\Sigma P_i} \qquad (11)$$

$(\Delta v)_i$ and $(\Delta q_s)_i$ were sampled on transects behind and upwind of the fence systems, respectively. P_i was sampled with well-sited recording precipitation gages.

Objective 1.c. (Test of design precipitation equation): Equation (8) was tested by comparing record from well-sited recording gages along I-80 with that of an unshielded recording gage installed at the site of the Elk Mountain cooperative observer gage (operated by the National Weather Service). The wind adjustment factor was tested by comparing the catch of the unshielded gage replicating the original Elk Mountain gage with the catch by a well-sited and shielded gage nearby. The elevation adjustment factor was tested by relating the catch of the various gages along I-80 to their elevation. The predicted mean winter precipitation along the highway (9.6 inches) used in the original snow fence system design was checked by comparing the 1971-72 winter's catch by the unshielded Elk Mountain gage with the average precipitation measured with the gage network along the highway.

Objective 2 and 3. a-c. (Determination of fence capacity and evaluation of fence performance): All of these objectives were accomplished by observing and measuring snow storage behind all fence systems near the time of peak accumulation. In general, if design criteria were adequate, all systems should contain about the same percentage of their design capacity. Systems with lesser degrees of saturation were examined to provide possible explanations for substandard performance. Of course the effectiveness of the fences was easily determined by comparing snow accumulation in the right-of-way downwind of the fences with conditions observed the winter before fencing was installed.

The 25H spacing factor was judged adequate if downwind fences appeared to behave as lead fences once upwind structures were filled to capacity. If a lead fence is full, the second fence should contain significantly more snow than the third fence in the series, and so on. When fences are spaced too closely, drift growth behind the second and third fences is approximately equal and reflects only the redeposition of snowfall between barriers.

Objective 3.d. (Evaluation of effects on visibility and ice formation.): Aerial and ground photographs of roadway visibility and ice conditions were made during several drifting events. In

addition to still photographs, a truck-mounted 16-mm movie camera was used to document visibility and ice conditions downwind of the fence systems.

Objective 4. (Fence efficiency as a function of snow accumulation): The efficiency of the lead 8-ft fence at Cooper Cove (System 1) was determined from the relative performance of the three rows of fencing. A method of calculation was used to estimate the escape of snow past the lead fence, whereby the change in water-equivalent storage behind the second fence, $(\Delta v)_2$, was assumed to be comprised of: a) the escape of snow past fence 1, and b) the relocation of precipitation falling between fences 1 and 2. This latter factor can be calculated in two ways. First, the catch by fence 3 $(\Delta v)_3$ can be assumed to be due only to the relocation of precipitation falling between fences 2 and 3. The interfence precipitation contribution to $(\Delta v)_2$ can be assumed proportional to $(\Delta v)_3$ and the relative spacing; for example, at System 1 fences 1 and 2 are 200 feet apart, and fences 2 and 3 are spaced 300 feet. Thus, the contribution of precipitation falling between fences 1 and 2 is equal to 2/3 $(\Delta v)_3$, and the efficiency E_1 of the lead fence can be calculated as

$$E_1 = \frac{(\Delta v)_1}{(\Delta v)_1 + (\Delta v)_2 - 2/3\ (\Delta v)_3} \tag{12}$$

The second method of estimating the amount of precipitation falling between fences uses values recorded in a nearby precipitation gage. Thus, the efficiency of the lead fence over the interval $\underline{i}$ can be calculated from

$$E_1 = \frac{(\Delta v)_1}{(\Delta v)_1 + (\Delta v)_2 - \theta_i P_i r_1 - 1/2\ \theta_i P_i\ (r_1^2 / R_m)} \tag{13}$$

where r_1 is the spacing between fences 1 and 2 (200 feet).

Both methods (Eqs. 12 and 13) take into account the portion of the snowfall sublimating during relocation between barriers. Equation (12) has the advantage of simplicity, and does not require a measure of precipitation or θ. It will later be shown that in the case of this study, both approaches give essentially the same result.

STUDY SITES, INSTRUMENTATION AND MEASUREMENTS

Locations of all study sites and istruments are shown on maps in Appendix A. Features of the two instensive-study sites (Systems 1 and 23) are compared in Tabler 1, and Figures 2 and 3.

Table 1. Characteristics of the two fence systems selected for intensive study.

System Number	Name	Milepost	Elevation	Average groundslope for 3000' upwind	Vegetation	Fences
1	Cooper Cove	281	7760	1% to east	short-grass	1-8' 2-12' 1-8'
23	Elk Mountain	253	7360	3% to west	sage-brush	1-8' 1-10' 1-12'

At both sites, a recording anemometer/wind vane (MRI Model 1071) was installed with the cups at 2 meters above the ground (Fig. 4). Other instruments operated at both sites included a hygrothermograph, installed at 1.5 meters above the ground in a cotton-belt instrument shelter, and a Belfort pyrheliometer, mounted on the shelter roof (Figs. 2 and 3). In addition, a recording blowing snow gage of the type described by Tabler and Jairell (1971) was installed at both locations with the orifice 0.5 meters above ground (Fig. 5). The instrument area at Cooper Cove was located about 500 feet upwind of the lead fence, and that at Elk Mountain was about 900 feet upwind of the fence system. The above instruments were not required to attain the objectives listed earlier, but provided data to calculate sublimation rates using Schmidt's (1972) model. As will be seen later in this report, these data greatly enhanced the results from this study.

Three recording precipitation gages, and two non-recording gages, all equipped with alter shields, were installed in what appeared to be the most favorable sites between mileposts 281 and 255 (Figs. 6-7, Table 2, and Appendix A maps). Because the National Weather Service gage in Elk Mountain was moved in 1971, following the death of the cooperative observer, an unshielded recording gage was installed at the original location in order to provide the necessary comparison with the gage network employed in this study (Fig. 8). All gages were installed in September, and serviced weekly until May 1, 1972.

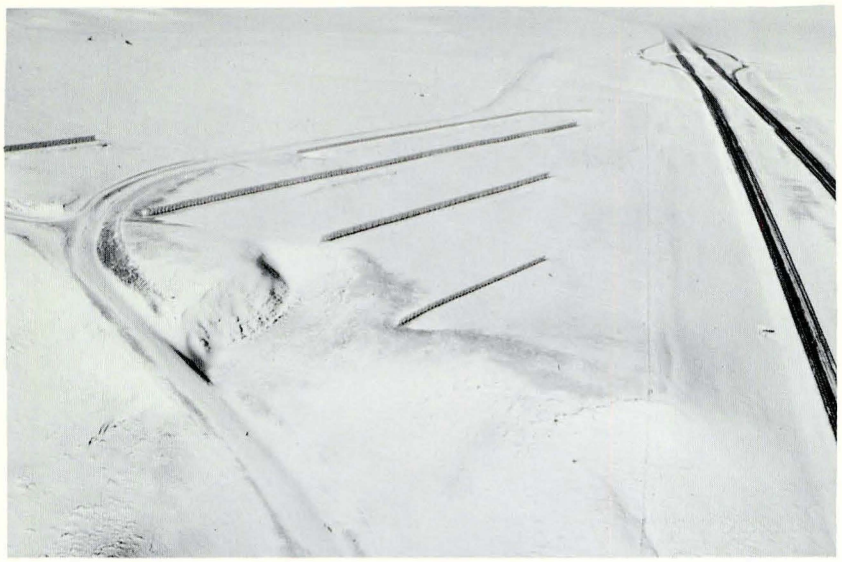


Figure 2. (Top) Aerial view of the Cooper Cove study site (System 1) on January 4, 1972. The fence at far left protects a cut on the county road. The lead fence is 8 ft tall, the second and third fences are 12 ft tall, and the last fence is 8 ft tall.
(Bottom) Typical view of the snow remaining at the Cooper Cove site after a drifting event. The shelter houses the hygrothermograph. (November 26, 1971).

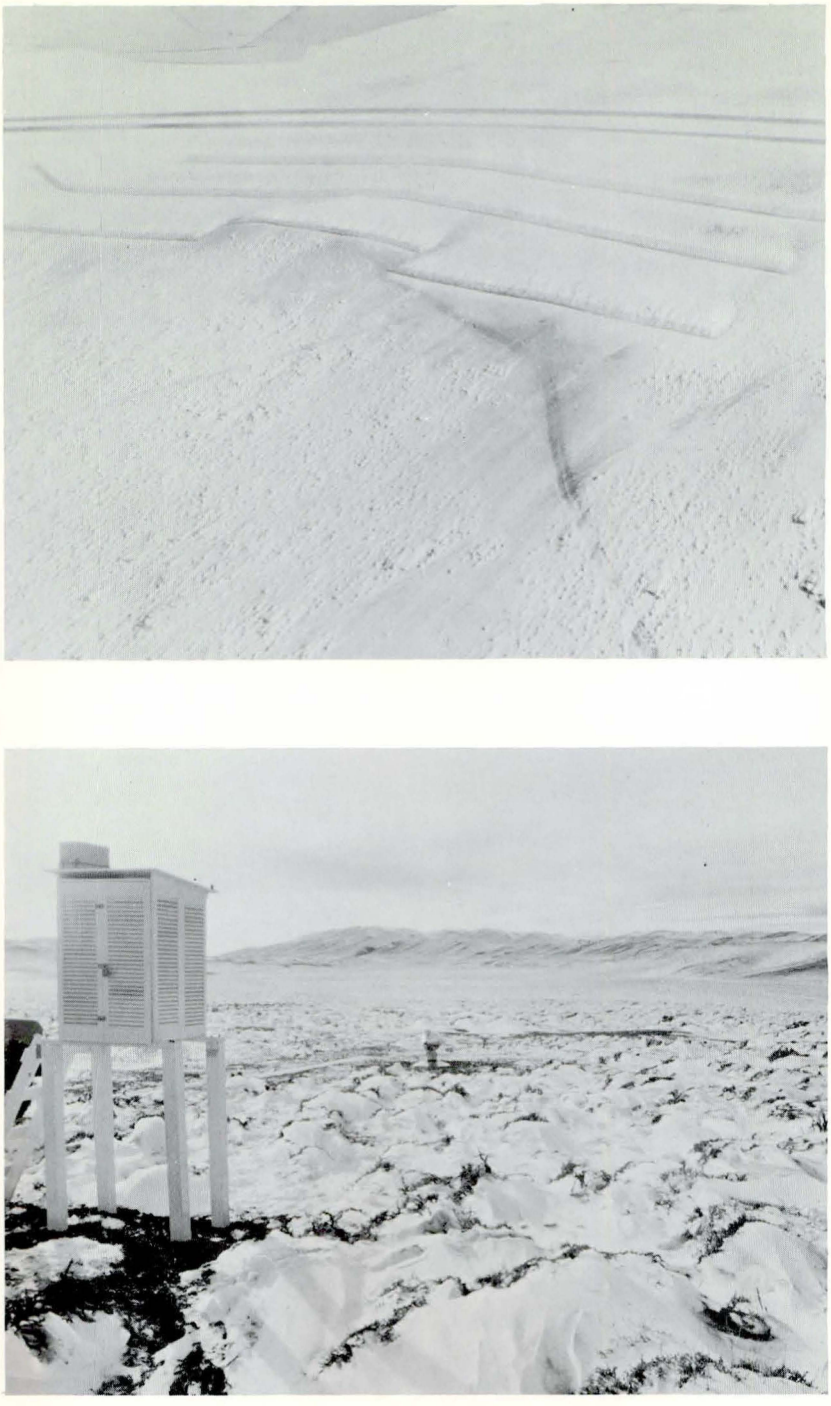
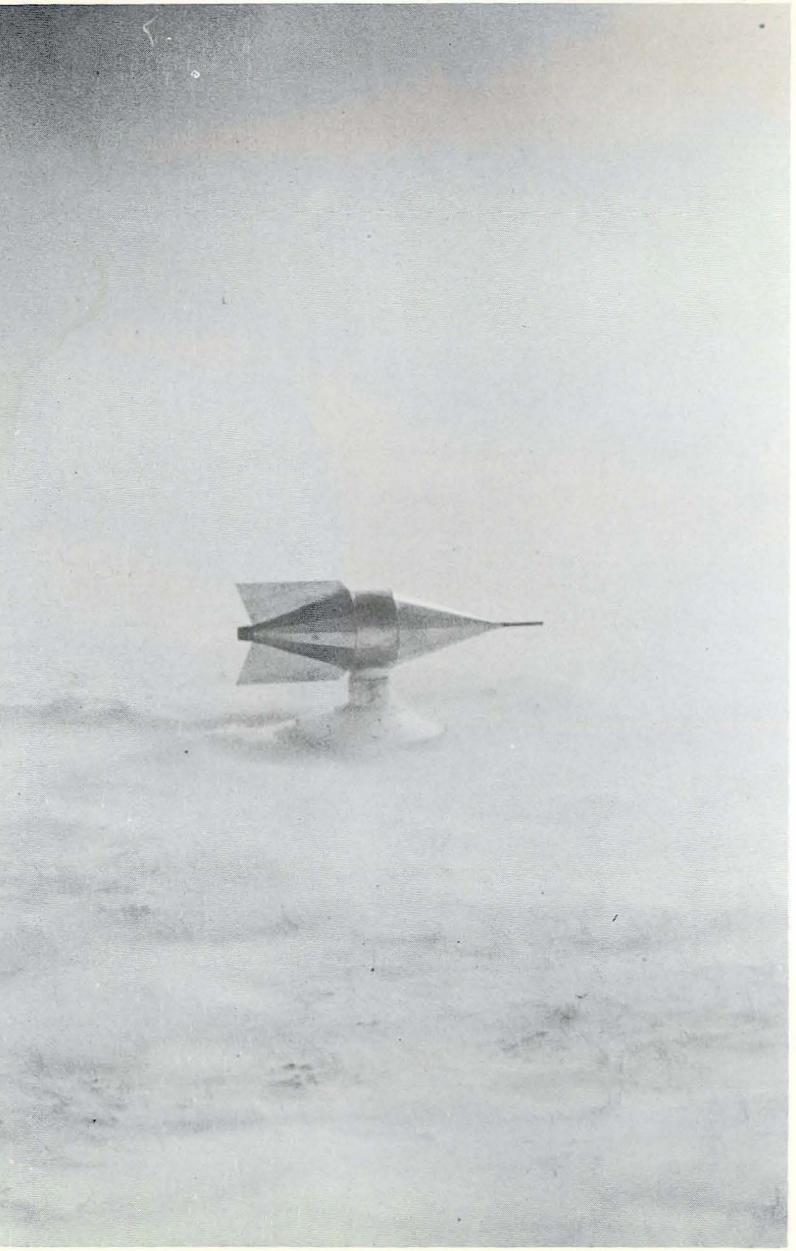


Figure 3. (Top) Aerial view of the Elk Mountain study site (System 23) on January 4, 1972. The lead fence is 8 ft tall, with a 6-ft section in the center. The second and third fences are 10- and 12 ft, respectively. (Bottom) Typical view of the snow remaining at the Elk Mountain Site after a drifting event (looking into wind). The instrument shelter houses the hygrothermograph. (December 13, 1971).

Figure 4. Recording anemometer/wind vane (MRI Model 1071) at the Cooper Cove study site (System 1). The instrument was installed with the cups at 2 m above the ground.



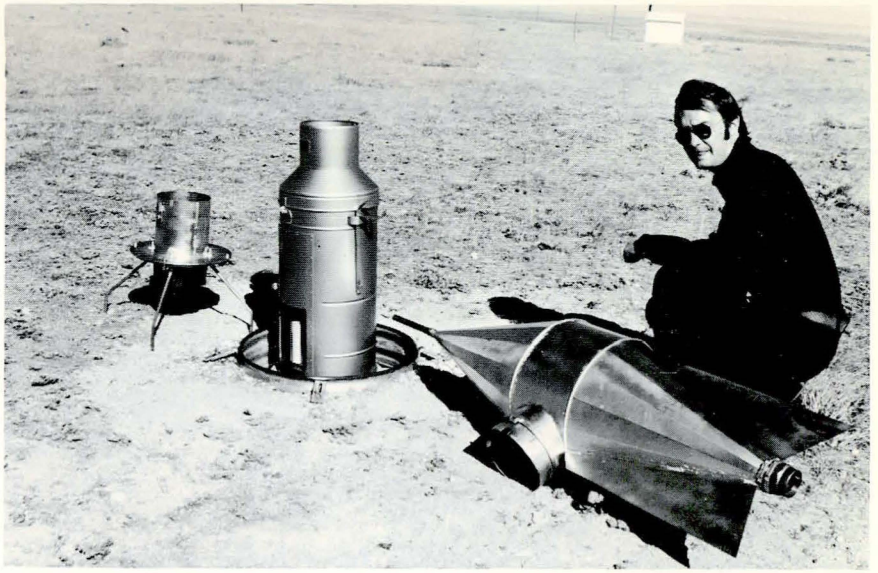
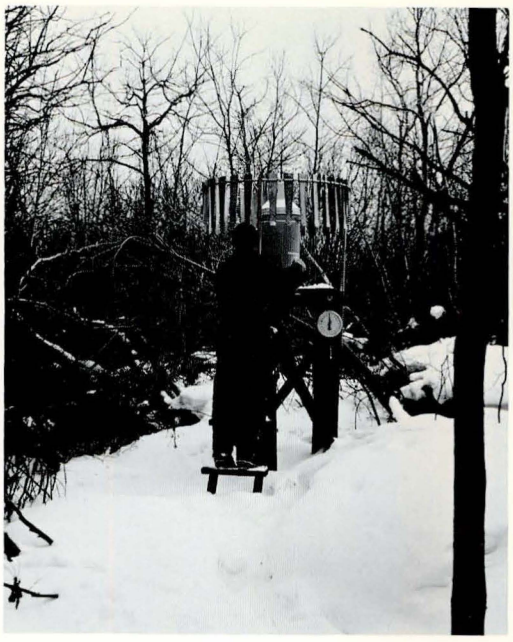


Figure 5. The recording, rotating snow flux gage operated at the Cooper Cove study site. The intake orifice has an area of about 3.14 cm^2 and is installed at 0.5 m above the ground. Mr. Keith Rounds, Public Information Officer for the Wyoming Highway Department, provides scale. Photo at left was taken on October 30, 1971.

Jankovsky Ranch
(1-27-72)



Foote Creek
(2-1-72)

Elk Mountain (1-31-72)

Figure 6. Views of the shielded recording precipitation gages.

Arlington

Woodedge

Figure 7. Views of the non-recording precipitation gages on February 1, 1972.

Figure 8. (Top) Original Elk Mountain precipitation gage at the G.E. Kleen residence, on February 6, 1971. As part of the National Weather Service cooperative observer network, the gage was operated at this location from 1956 to 1970. The gage was moved to a new location in 1971 following Mr. Kleen's death. Record published for this gage was used to estimate the long-term mean precipitation for the original snow fence design.

(Bottom) A recording gage, unshielded, was installed at the exact location of the original gage to provide a test of the precipitation estimate (January 31, 1972).

Table 2. Description of precipitation gage network operated during the 1971-72 winter

Gage name	Type	Location		Elevation	Description & remarks
		Legal description	Milepost		
Jankovsky Ranch	Recording, shielded, 5-ft tower	SE-1/4 SE-1/4 S19 T18N, R77W	282	7737	25-ft diameter opening in aspen and alder. 3% slope toward NE.
Woodedge	Standard can, shielded, 10-ft tower	NE-1/4 SE-1/4 S22 T18N, R78W	279	8210	25-ft diameter opening in pine. 8% slope toward NE.
Arlington	Standard can, shielded, 5-ft tower	SW-1/4 SE-1/4 S19 T19N, R78W	272	7650	100-ft diameter opening in cottonwood. 2% slope toward NE.
Foote Creek	Recording, shielded, 5-ft tower	NE-1/4 NE-1/4 S23 T19N, R79W	270	7755	Cleared opening 20-ft in diameter in dense aspen and alder. 4% slope toward NE.
Elk Mountain Shielded	Recording, shielded, 5-ft tower	NE-1/4 SW-1/4 S20 T20N, R80W	259	7250	20-ft diameter opening in cottonwoods. 2% slope toward NE.
Elk Mountain Unshielded	Recording, unshielded, 1-ft platform	NE-1/4 NW-1/4 S29 T20N, R80W	259	7275	In back yard of G. E. Kleen residence, at site of National Weather Service gage from 1956-70.

Snow depth and water-equivalent were sampled behind the two intensive-study fence systems after each major event, or at periods no greater than two weeks, during the accumulation season. Snow depths were probed at 10-ft intervals along four permanent transects at Cooper Cove (System 1) and three premanent transects at Elk Mountain (System 23). Transects at Cooper Cove were spaced 32 ft apart near the center of the north half of the system. The fence arrangement at this location was an 8-ft lead fence, followed by two 12-ft fences spaced at 200 and 300 ft, respectively (Fig. 2). Transects at Elk Mountain were spaced 48 ft apart at the center of the south half of the system. The fence arrangement at this location was an 8-ft lead fence, followed by a 10-ft fence spaced at 220 ft, followed by a 12-ft fence spaced at 235 ft. At both locations, each of these permanently marked transects passed through all three fences.

Water-equivalent was sampled with a Mount Rose sampler at 10-ft intervals along one transect at each fence. This density transect was chosen at randown (without replacement) on each sampling date to avoid sampling old holes. Snow storage upwind of both fence systems was sampled by probing snow depths at 10-ft intervals along a single permanent transect extending 1000 feet upwind of the lead fence, and water-equivalent was sampled at 10 or more points selected at random along these transects.

To determine the performance of all other fence systems (Objectives 2 and 3 a-c.), identical procedures were used to sample snow accumulations behind all other fences installed in 1971, except that these measurements were made on only one date near the time of maximum snow retention.

RESULTS

General.--Detailed results of this study must be prefaced by the general statement that the snow fence systems proved to be extremely effective in preventing snow accumulation on the right-of-way. The methods used to estimate the amounts of blowing snow available at the control sites proved very successful, although this success was due in part to compensating errors in the estimates of values used in the design equations. The largest error in the original design was an underestimate of the snow storage capacity of the highway department's new standard-plan fence.

A new and important discovery was that the fences dramatically improved visibility and reduced ice formation on the road surfaces.

The detailed results that follow provide the information necessary to optimize the efficiency and economy of future fence systems.

Snow accumulation at Systems 1 and 23, and evaluation of methods used to estimate amounts of blowing snow.--Snow accumulation at the

two intensive-study sites (Fig. 9) began with the storm of October 27, and reached a peak on February 18, with only small amounts of net ablation (melting and evaporation) over the interim (see Appendix B for specific data). The winter ended as early as it began, however, and March passed without a single drifting event. Peak accumulation at Cooper Cove (System 1) was 842 ft^3 water-equivalent per lineal ft, or about 64% of that system's design capacity. Peak storage at the Elk Mountain site was 529 ft^3 water-equivalent per lineal ft, or 47% of the design capacity. Although the 1971-72 winter was unusually mild, at least at the two study sites, there was ample data to meet study objectives.

The most telling test of the method used to estimate amounts of blowing snow is the plot (Fig. 10) of actual snow storage behind the two fence systems versus the accumulation that would be predicted from Eq. (3). The agreement between actual and predicted amounts is spectacular, even though it is in some degree due to compensating errors.

The estimate originally used for the transport distance R_m in the design Equation (4)

$$q_b = 1/2\ R_m\ (\ P - q_s)$$

was 3300 feet, based on another study that was cited earlier in this report. To test this estimate, R_m was calculated from each drifting period at both study sites. Solving Eq. (6) for R_m (with a three-fence system),

$$R_m = 1/2\left\{ \left[\frac{2Q}{\theta P} - 2r_1 - 2r_2\right] + \left[\left(\frac{2Q}{\theta P} - 2r_1 - 2r_2\right)^2 + 4(r_1^2 + r_2^2)\right]^{1/2} \right\} \quad (14)$$

The snow transfer coefficient (θ) was determined by measuring the residual snow upwind of the fence systems at the end of each drifting period (Appendix C). The results of these measurements and calculations are given in Tables 3 and 4.

Of the two study sites, Cooper Cove provided the best measure of R_m; the sagebrush vegetation at Elk Mountain at times made calculation of the transport distance impossible. For example, on two dates (Table 4) the increase in snow storage in the brush upwind of the fence system was greater than the interval precipitation -- presumably due to the relocation of older snow from behind the brush farther upwind than where the residual snow measurements were made. Another complicating factor was the melt and evaporation of the residual snow carried over between successive measurements, making accurate determination of the snow transfer coefficient impossible.

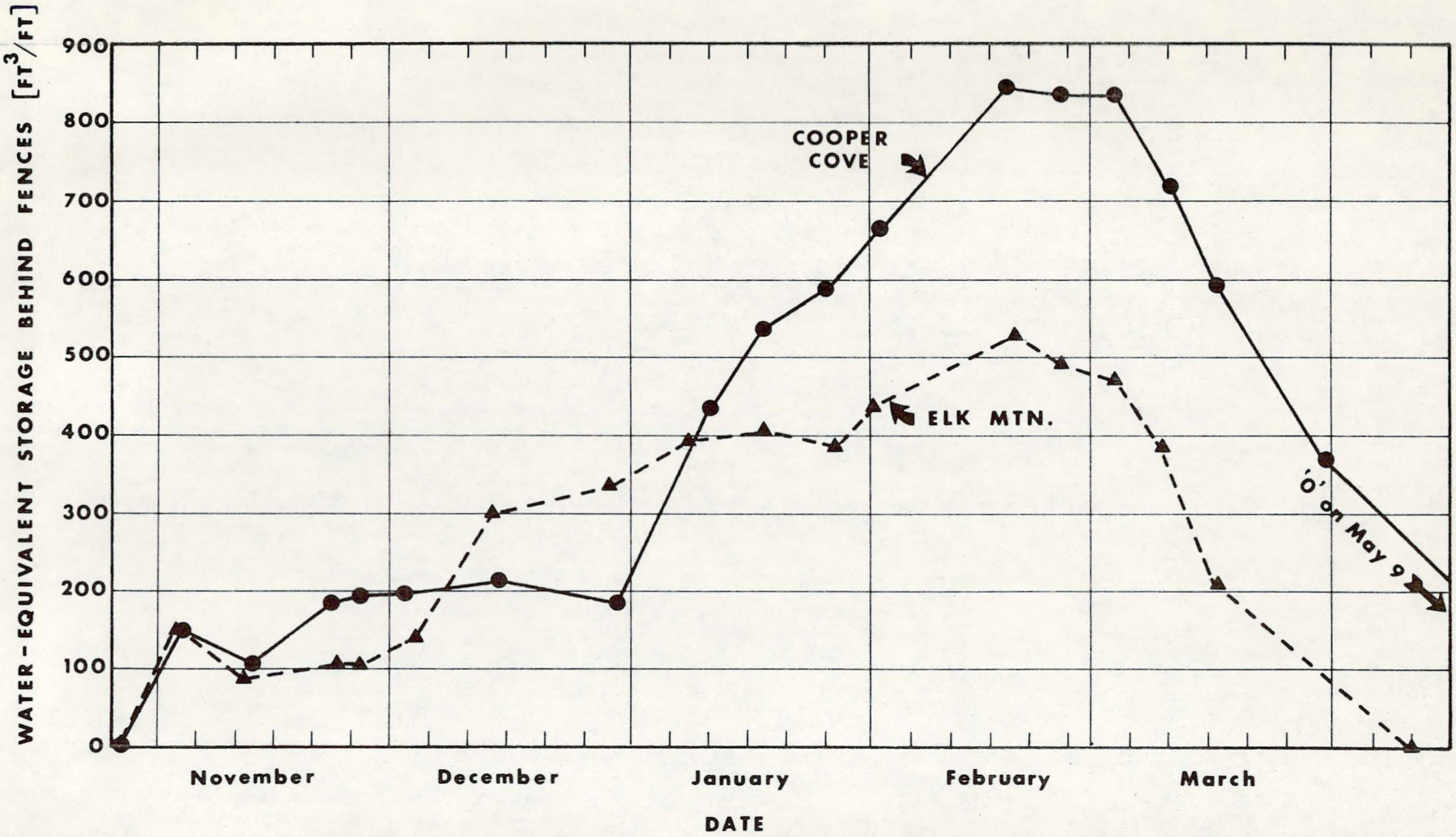


Figure 9. Water-equivalent storage at the Cooper Cove (System 1) and Elk Mountain (System 23) study sites during the 1971-72 winter.

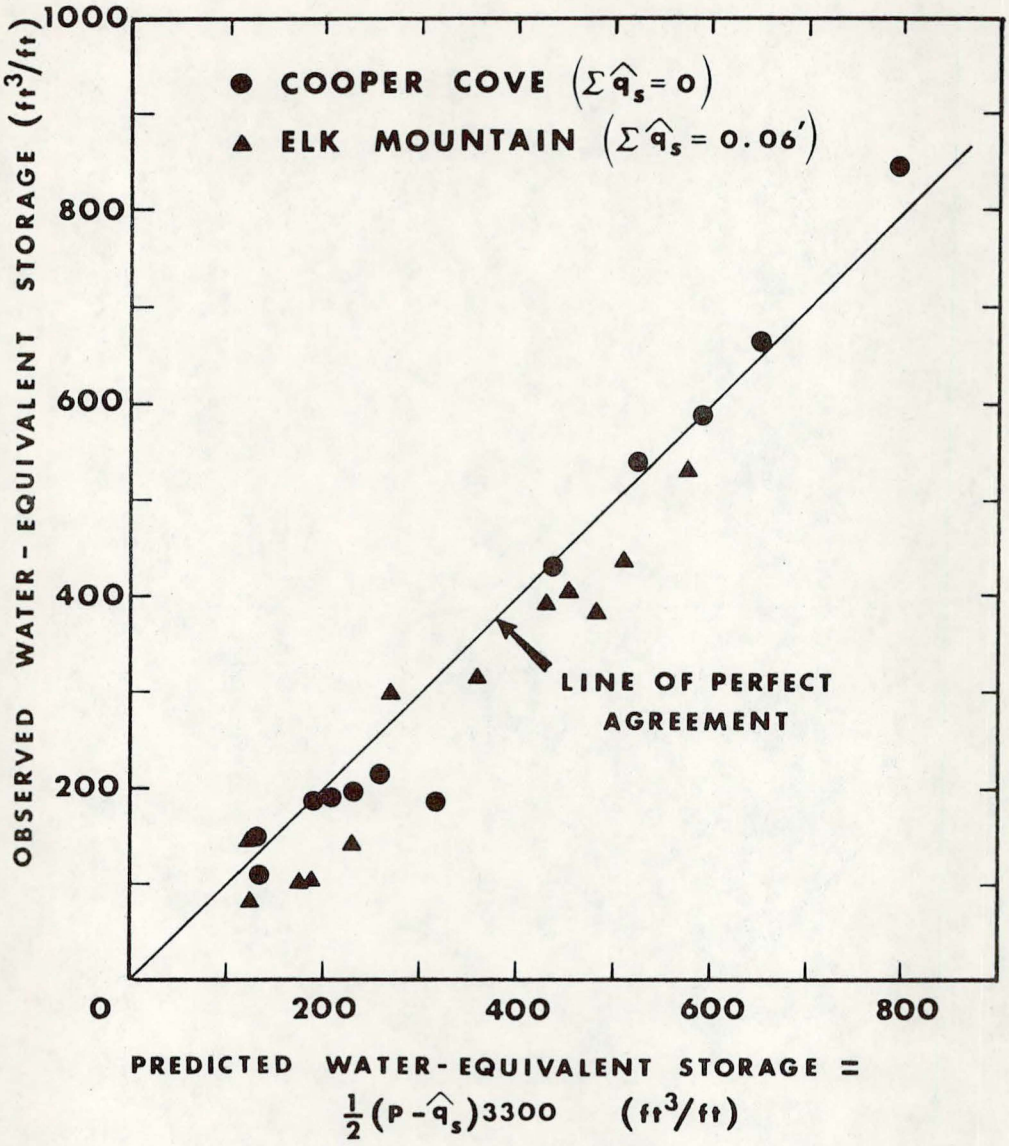


Figure 10. Observed versus predicted water-equivalent storage behind the fence systems at Cooper Cove (System 1) and Elk Mountain (System 23).

Table 3. Precipitation, change in water-equivalent storage behind fence system, residual upwind snow, and transport distance for all sampling intervals at Cooper Cove study site

Period	Precipitation P_i	Change in residual upwind water-equiv. $(\Delta q_s)_i$	$\theta_i \left[\frac{P_i-(\Delta q_s)_i}{P_i}\right]$	Change in water-equiv. storage behind fences $(\Delta v)_i$	Transport distance 1/ $(R_m)_i$
	inches	inches		ft^3/ft	ft
10/27 - 11/1/71	0.94	?	?	147.1	?
11/1 - 11/12	0.02	?	----	- 46.2	----
11/12 - 11/22	0.41	0.14	0.66	82.7	6348
11/22 - 11/26	0.15	0.05	0.67	9.6	1386
11/26 - 12/2	0.16	0.02	0.88	5.7	348
12/2 - 12/14	0.18	0	1.00	16.5	1300
12/14 - 12/29	0.43 (rain)	0.02	0.95	- 29.4	----
12/29 - 1/10/72	0.88	0.06	0.93	247.1	6270
1/10 - 1/17	0.63	0.04	0.94	106.3	3347
1/17 - 1/25	0.50	0.04	0.92	47.4	1555
1/25 - 2/1	0.44	0.04	0.91	75.9	3582
2/1 - 2/17	1.05	0.10	0.90	179.8	3602
End accumulation period					
Totals	5.79	0.51		842.5 (net)	
Weighted means			0.89		4488

1/ $$(R_m)_i = 1/2\left\{\left[\frac{2(\Delta v)_i}{\theta_i P_i} - 1000\right] + \left[\left(\frac{2(\Delta v)_i}{\theta_i P_i} - 1000\right)^2 + 520{,}000\right]^{1/2}\right\}$$

This calculation accounts for interfence precipitation and its sublimation during relocation.

Table 4. Precipitation, change in water-equivalent storage behind fence system, residual upwind snow, and transport distance for all sampling intervals during the accumulation period at the Elk Mountain (System 23) study site.

Period	Precipitation P_i	Change in residual upwind water equiv. $(\Delta q_s)_i$	$\theta \left[\frac{P_i-(\Delta q_s)_i}{P_i}\right]$	Change in water-equiv. storage behind fences $(\Delta v)_i$	Transport distance[a] $(R_m)_i$
	inches	inches		ft^3/ft	ft
10/27 - 11/2/71	1.14	0.60	0.48	150.3	5700
11/2 - 11/11	0.00	-0.60	----	- 64.9	----
11/11 - 11/23	0.54	0.40	0.26	19.2	2415
11/23 - 11/26	0.08	-0.23	1.0[e]	0	----
11/26 - 12/3	0.34	0.91	>1.0	35.8	2530[b]
12/3 - 12/13	0.40[c]	0.05	0.88	160.2	10,034
12/13 - 12/28	1.02[c]	0.15	0.85	35.1	----
12/28 - 1/7/72	0.69	0.27	0.61	59.3	2513
1/7 - 1/17	0.21	0	1.0	10.6	506
1/17 - 1/26	0.29	-0.24	1.0[e]	- 18.6	----
1/26 - 1/31	0.25	0.43	<0.0	52.1	5010[b]
1/31 - 2/18 End accumulation period	0.67	-0.04	1.0[e]	90.2	3233
Totals	5.63	2.81 (+ only)		529.3 (Net)	

a/ $$(R_m)_i = 1/2\left\{\left[\frac{2(\Delta v)_i}{\theta_i P_i} - 910\right] + \left[\left(\frac{2(\Delta v)_i}{\theta_i P_i} - 910\right)^2 + 414{,}500\right]^{1/2}\right\}$$

This calculation accounts for interfence precipitation and its sublimation during relocation.

b/ Assumes $\theta = 1.0$

c/ Includes 0.52 inches of rain

By comparison, the short-grass vegetation and smooth terrain at the Cooper Cove study site made this location nearly ideal for determining the transport distance from Eq. (14). On all but two dates, the residual snow from the previous sampling date had disappeared by the beginning of the next drifting period. This ability to "start from zero" greatly improved the reliability of the estimate for Θ (or q_s).

The transport distance (R_m) at Cooper Cove varied from 348 ft to 6348 ft, with a weighted mean value of 4488 ft. This measured distance is 36% greater than the original 3300-ft estimate. Compensating for this underestimate, however, was the measured snow transfer coefficient of 0.89 (again a weighted mean), to be compared with the original assumption that Θ=1.0 at Cooper Cove. The average water-equivalent of the residual snow (upwind of the fence systems) when the vegetation storage was satisfied was about 0.06 inches at Cooper Cove.

The estimate of natural upwind storage originally used in the design of System 23 (Elk Mountain) was 197 ft^3/ft water-equivalent totalled over the 3300-ft transport distance, which would equal 0.71 inches of precipitation (with Θ therefore = 0.92). Although average brush storage capacity was measured to be 0.54 inch at the Elk Mountain study site, ablation of the residual snow during the winter made room for additional storage, with the result that residual snow upwind of the Elk Mountain fence system totalled 2.81 inches over the accumulation season. This yields a snow transfer coefficient of 0.50.

Thus, the underestimate of natural storage upwind at both study sites helped compensate for the initial underestimate of R_m. Another compensating factor was melt and evaporation of the snowdrifts during the winter. Although winter ablation was not taken into account directly in the original design, this factor was considered as protection against possible underestimates for snow transport. Over the 1971-72 winter, net water-equivalent ablation of the drifts from the commencement of accumulation until the time of peak storage (Fig. 9) amounted to 75.6 ft^3/ft (or about 8% of gross accumulation) at Cooper Cove, and 83.5 ft^3/ft (14% of gross accumulation) at the Elk Mountain site. These values become more meaningful when compared with results from an earlier study on Pole Mountain (east of Laramie) which showed that 10% of the gross accumulation behind a single 12-1/2-ft-tall fence was lost to ablation during the 1970-71 accumulation season (which extended from October 9, 1970 to March 26, 1971).

Analysis of drifting events.--Based on record from the recording flux gages, drifting occurred during 299 hours (7.9% of the time)

between October 27 and April 1 at the Cooper Cove study site, and during 237 hours (6.3% of the time) over the same period at Elk Mountain. Dates of drifting at both sites are shown in Figure 11.

The flux gages used in this study have not been calibrated; indeed, the factors affecting the distribution of blowing snow above the ground are so complex that there would seem little possibility for relating the small sample at 0.5 meters to the total mass flux. However, Figure 12 shows that the mass transport sample from the flux gage at Cooper Cove corresponded well with the incremental accumulation behind the fence system. The relationship at Elk Mountain is not as well defined, for reasons not understood at this time.

The primary utility of the flux gage record is that it provides the basis for determining weather conditions during drifting. This information, in turn, can be used to calculate sublimation rates of blowing snow. The mean value for any given weather variable ($\bar{Y}$) over the season, or other period of time, was obtained from

$$\bar{Y} = \frac{\Sigma FY}{\Sigma F} \tag{15}$$

where Y is any given mean hourly weather variable and F is the hourly snow transport at 0.5-m height. Mean weather conditions during drifting for each sampling period at the two study sites are given in Appendix D, and mean seasonal values are shown in Table 5. Figures 13 and 14 present frequency histograms for the two sites showing how the 0.5-m flux was distributed with respect to size of events, month, time of day, air temperature, relative humidity, total incoming solar radiation, and windspeed.

A mathematical model for sublimation of wind-blown snow has recently been published (Schmidt, 1972). A simplified approximation of Schmidt's model estimates a particle's average sublimation rate (dm/dt), in grams per second, from

$$\left[\frac{dm}{dt}\right]_{\bar{X}_s} \doteq \frac{8.95\cdot10^{-4}\bar{X}_s(1 + 37\bar{X}_s)(1 - RH/100) + 5.22\cdot10^{-7}(85.6 - T)\bar{X}_s^2 S}{T^2 - 8.2T + 254} \tag{16}$$

for the temperature range 0 to -20°C, at 750 mb pressure. The factors required to evaluate this expression are (1) relative humidity (RH) in percent, (2) temperature (T) in °C, (3) solar radiation (S) in cal/cm^{2}hr, and (4) the average sublimation particle diameter ($\bar{X}_s$) in centimeters.

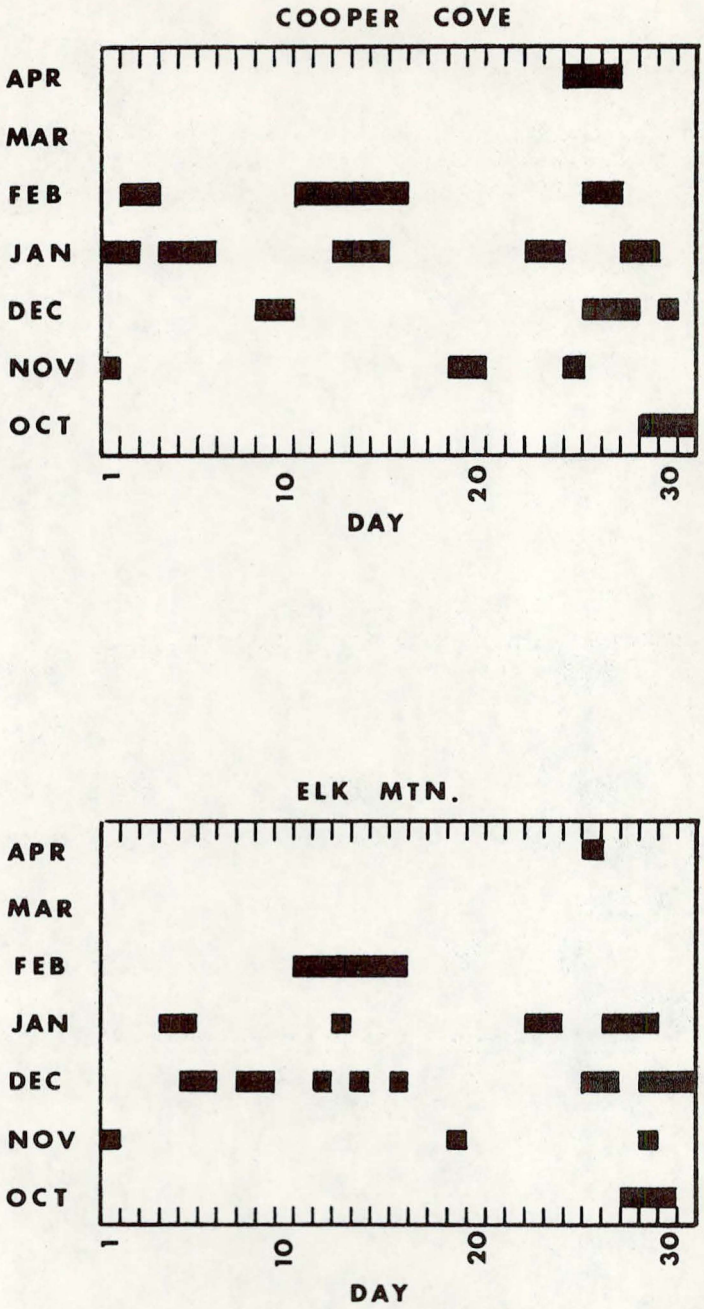


Figure 11. Dates of drifting at the two study sites over the 1971-72 winter.

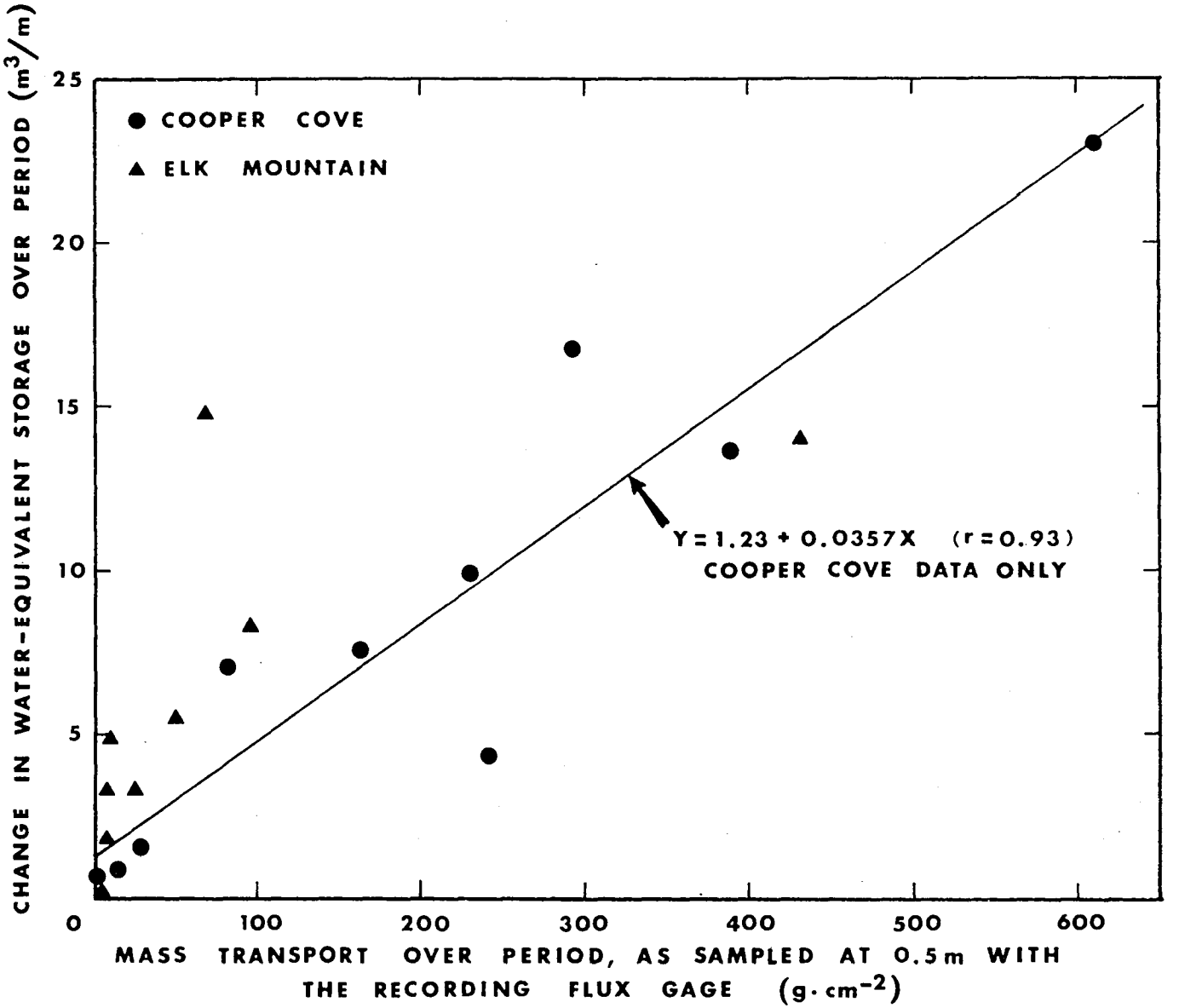


Figure 12. Relationship between incremental water-equivalent storage behind the Cooper Cove fence system, and snow transport at 0.5 m as measured in the recording snow gage of Figure 5.

Table 5. Seasonal mean (weighted) weather conditions during drifting at the two study sites over the 1971-72 winter

Factor	Cooper Cove (System 1)	Elk Mountain (System 23)
Wind speed at 2-m height ($m \cdot sec^{-1}$)	16.4	13.1
Wind azimuth (deg. cw from True North)	261	258 (240 prevailing)
Relative humidity at 2 meters (%)	80	83
Air temperature at 2 meters (°C)	-8.5	-7.0
Incoming radiation, shortwave ($cal \cdot cm^{-2} \cdot hr^{-1}$)	16.0	12.3

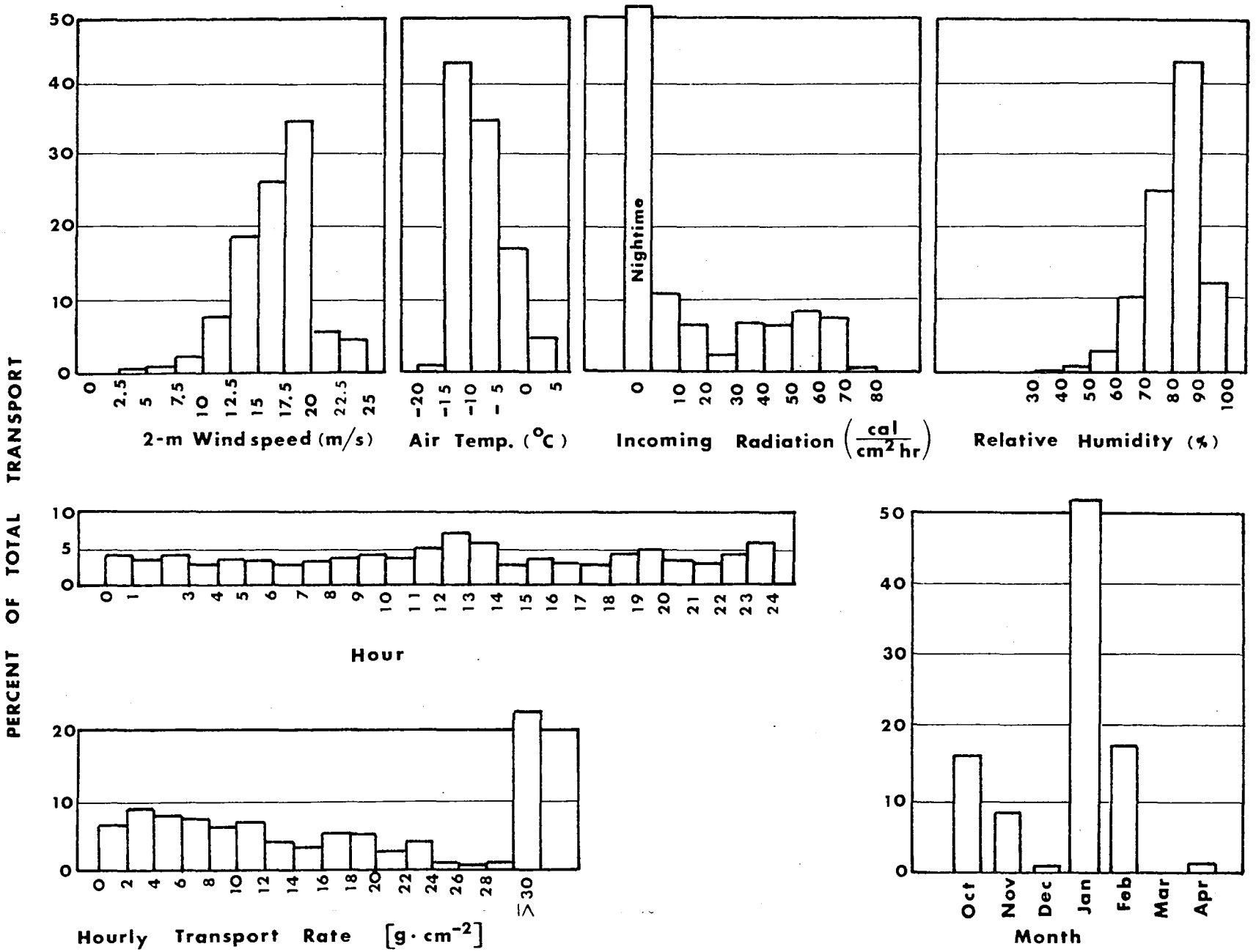


Figure 13. Percentage distribution of selected factors during all drifting events at the Cooper Cove study site over the 1971-72 winter.

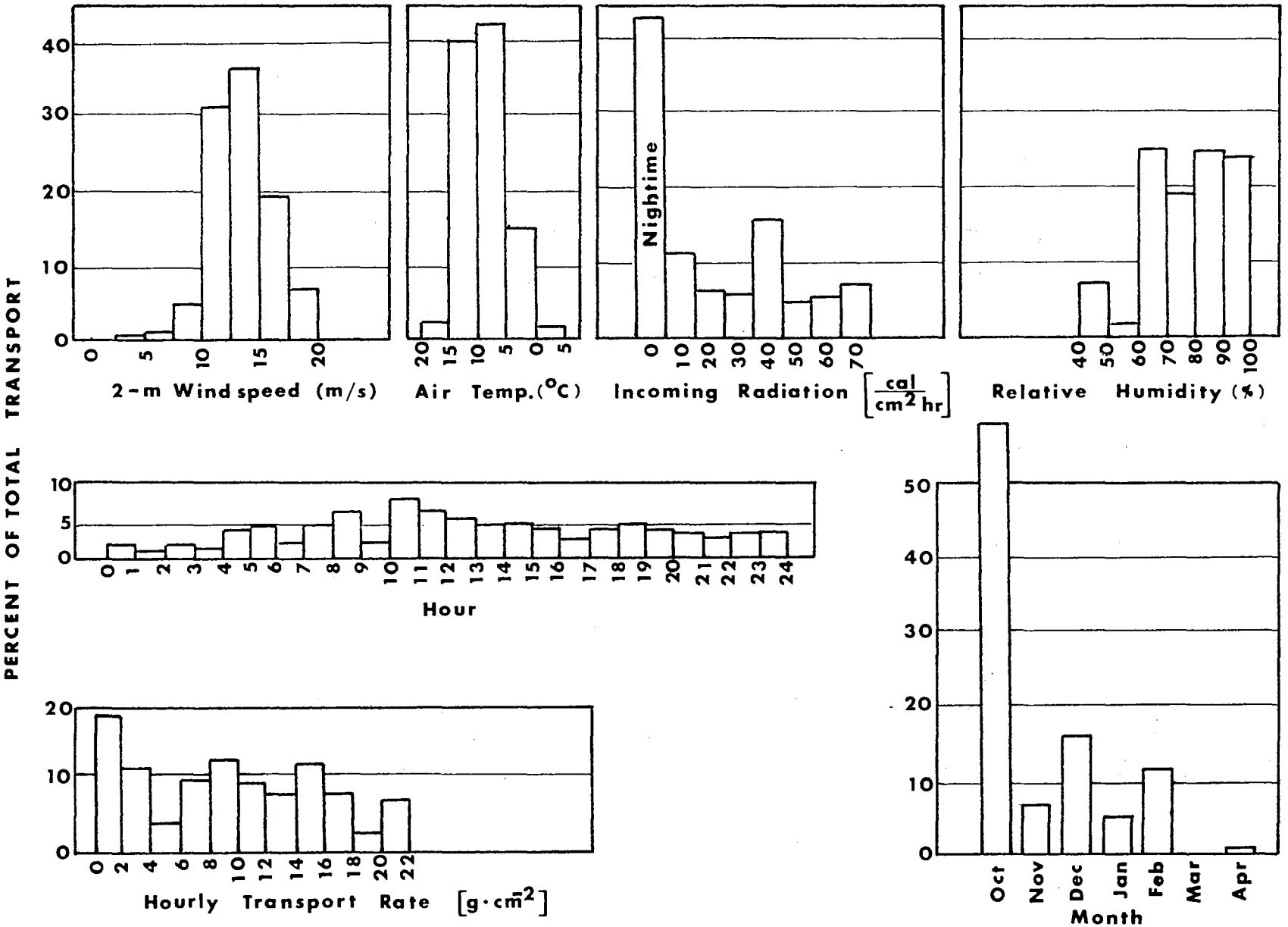


Figure 14. Percentage distribution of selected factors during all drifting events at the Elk Mountain study site over the 1971-72 winter.

Table 6. Transport distances calculated from Eq. (14), and corresponding particle diameters given by Eq. (17), for all measurement periods over the accumulation season at Cooper Cove. Data used to calculate particle size are given in Appendix D.

Period	Transport distance, R_m (meters)	Mean snow particle diameter, $\bar{X}$ (cm)
10/27 - 11/1/71	?	?
11/1 - 11/12	0	---
11/12 - 11/22	1935	0.0125
11/22 - 11/26	422	0.0090
11/26 - 12/2	106	?[a]
12/2 - 12/14	396	0.0085
12/14 - 12/29	0	---
12/29 - 1/10/72	1911	0.0103
1/10 - 1/17	1020	0.0087
1/17 - 1/25	474	0.0078
1/25 - 2/1	1092	0.0097
2/1 - 2/17	1098	0.0110
Weighted means for season	1368	0.0109

a/ Although there was a small (5.7 ft^3/ft) increase in water-equivalent storage behind the fence system over this period, no flux was recorded by the drift gage; thus, there is no basis for determining weather conditions during the drifting event.

With certain additional assumptions, Eq. (16) can be used to calculate the transport distance R_m using the expression (Tabler and Schmidt, 1972)

$$R_m = \frac{0.715\ (\bar{U}_2 - 5.87)\ \bar{X}^3}{(dm/dt)_{\bar{X}}} \qquad (17)$$

where R_m is in meters, $\bar{U}_2$ is the mean hourly wind speed at 2 meters, and (dm/dt) is calculated from Eq. (16) with average particle size $\bar{X}$.

Because particle size was not measured in this study, Eq. (17) was used instead to calculate the average particle size required to yield the observed values of R_m, as calculated from Eq. (14). These values for particle diameter, shown in Table 6, were calculated only for the Cooper Cove site, where the R_m values were the most reliable. Calculated diamters were notably constant over the winter, ranging from 0.0125 to 0.0078 cm. The mean value for the season was 0.0109 cm, which is in close agreement with the majority of published values for the size of wind-blown snow particles (Mellor, 1965). These results further substantiate the method used to estimate the amounts of blowing snow at the control sites on I-80.

Equation (17) is also useful for comparing the relative transport distances at the two study sites, and thus can be used to estimate the transport distance at the Elk Mountain site. Assuming, for example, snow particles to be the same size at both locations, Eq. (17) indicates the transport distance at Elk Mountain to be about 3300 ft, or 74% of that at Cooper Cove. Interestingly, this was the value used for the orginal estimates of blowing snow on I-80. The shorter transport distance at Elk Mountain, as compared to Cooper Cove, is principally due to the lower windspeeds at Elk Mountain (Table 5).

The actual measurement of particle size is difficult, and it is hard to conceive of a method, other than that used here, to sample the mean particle size over the entire vertical profile of blowing snow. Anticipating the development of such a method, however, it is useful to express transport distance as a function of average particle size, as calculated from Eq. (17) and the mean values for the weather factors. Results for the two study sites are shown in Figure 15. Over the most probable range of particle diameters ($\bar{X}$), 0.005 to 0.015 cm, the curves in Figure 15 can be approximated by

$$\text{Cooper Cove}: \quad R_m \doteq 4.091 \cdot 10^6\ \bar{X}^{1.77} \qquad (18)$$

$$\text{Elk Mtn.}: \quad R_m \doteq 3.019 \cdot 10^6\ \bar{X}^{1.77} \qquad (19)$$

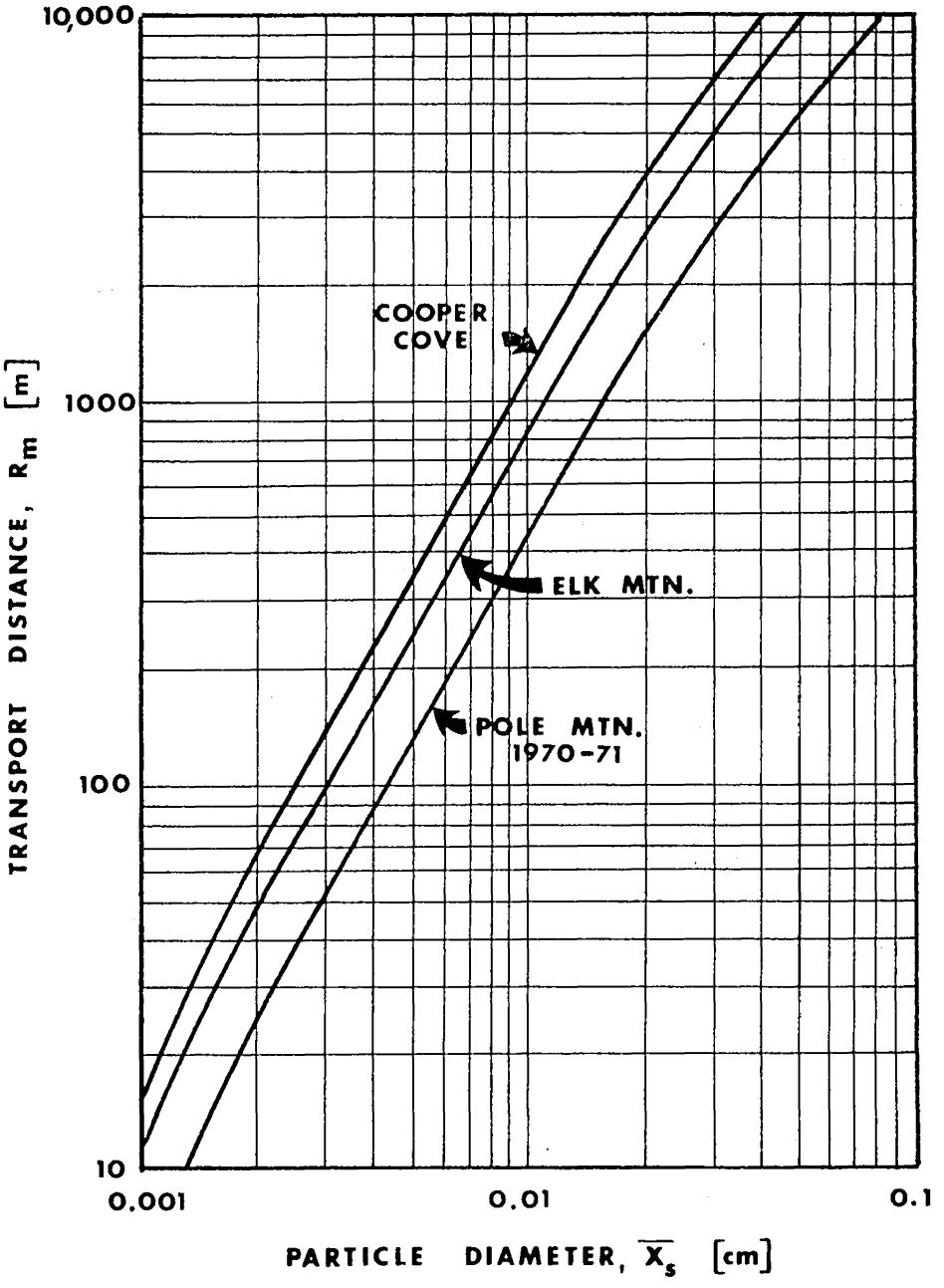


Figure 15. Transport distance as a function of particle diameter, calculated from Eq. 17. Results from both study sites along I-80 are shown, as well as those from an earlier study on Pole Mountain (Tabler and Schmidt, 1972).

where $\overline{X}$ is in cm and R_m is in meters. These results can be compared with those from an earlier study on Pole Mountain (Tabler and Schmidt, 1972) where

$$\text{Pole Mtn.} : \quad R_m \doteq 1.659 \cdot 10^6 \overline{X}^{1.78} \tag{20}$$

It appears that over this range of particle sizes, transport distance is proportional to the 1.77 power of particle diameter. It is likely that this could be demonstrated mathematically from Eq. (17), but empirical results were necessary to demonstrate the possibility. Perhaps future empirical studies will find an index to transport distance by relating the coefficients in Eqs. (18-20) to weather conditions.

Evaluation of Precipitation Estimate.--Daily precipitation amounts at the recording gages are given in Appendix E. Monthly totals for all gages are shown in Table 7. Average precipitation for the highway was calculated as the mean of the three recording gages. Total precipitation was 6.79 inches for the accumulation season (October 26, 1971 to February 29, 1972), and 7.58 inches for the period October 26 to March 31, 1972. This last value is 79% of the estimated long-term mean (9.6 inches) used in the design. The probability analysis made for last year's report shows that the 7.58-inch value would be exceeded 7 years out of 10.

In general, the original estimate of the long-term mean was verified by study results, but again this success was due to compensating errors. The winter-long wind adjustment factor for the unshielded National Weather Service gage at Elk Mountain was originally estimated to be 1.5 (Eq. 8). The ratio between shielded and unshielded gages derived from this study was 6.54/5.15 = 1.27.

The original estimate for an elevation adjustment factor in winter precipitation was 1.1 inches per 1000-ft rise in elevation while that derived from this study was 5.0 inches per 1000-ft (Fig. 16). In the original design, the mean elevation of the highway was assumed to be about 1000 ft above the Elk Mountain gage (elevation 7275 ft); but a closer estimate of the contributing area's mean elevation between mileposts 247 and 281 would be 7550 ft).[4] Thus the original 1.1-inch adjustment factor is to be compared to an "actual" value of 1.4 inches, based on the one winter's measurements.

The revised equation for mean winter (November 1 to April 1) precipitation then becomes

$$\overline{P} = 1.3 \text{ (Elk Mtn. Station Mean + 1.4)} \tag{21}$$

[4] Average elevation of the east-bound lane right-of-way between mileposts 247 and 281 is about 7500.

Table 7. Monthly precipitation (inches) at all gages during the 1971-72 winter. Elevations are shown in parentheses.

Month (or period)	Jankovsky Ranch RRG (7737)	Woodedge SAG (8210)	Arlington SAG (7650)	Foote Creek RRG (7755)	Elk Mtn. Shielded RRG (7250)	Elk Mtn. Unshielded RRG (7275)	Mean of shielded RRG
October 26 - 31	0.90	0.88	0.92	1.03	1.16	0.88	1.03
November	0.81	1.39	1.13	1.26	0.94	0.73	1.01
December	0.70	1.50	1.45	1.84	1.62	1.56	1.37
January	2.37	3.22	2.32	1.83	1.27	0.92	1.87
February	1.73	2.43	1.80	1.79	0.99	0.68	1.51
March	0.75	1.25	0.92	1.04	0.56	0.38	0.79
Total for accumulation season (10/26 - 2/29/72)	6.51	9.42	7.62	7.75	5.98	4.77	6.79
Total for winter (10/26 - 3/31)	7.26	10.67	8.54	8.79	6.54	5.15	7.58

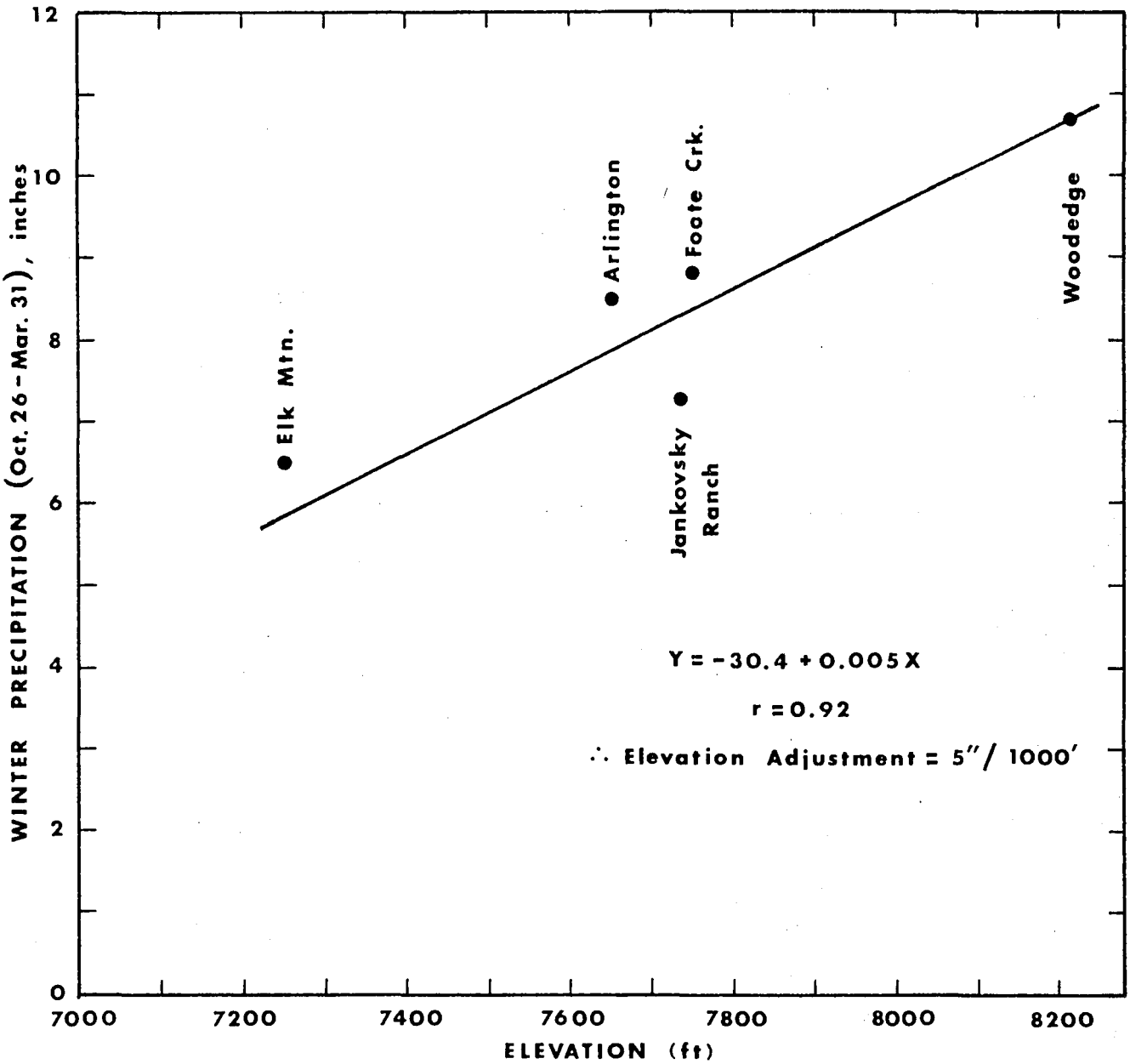


Figure 16. Precipitation as a function of elevation, for the gage network along I-80 during the 1971-72 winter.

yielding a revised estimate for the long-term mean of 8.7 inches. This is a downward adjustment of about 9% from the original estimate of 9.6 inches.

The strong dependency of precipitation on elevation along I-80 should be taken into account in the design of future fence systems by using the equation

$$\overline{P} = 6.9 + 0.005 \text{ (Elevation - 7275)} \qquad (22)$$

where $\overline{P}$ is mean winter precipitation, in inches.

Performance of All Fence Systems.--In general, the fences performed very well. Of the seventeen systems completed in 1971, only the Arlington Interchange separation experienced drifts requiring removal. No drifting snow accumulated on the mainline at any site protected by fencing. Figures 17 to 23 compare snow accumulations in the more troublesome cuts the winter before fencing, with conditions during the 1971-72 winter. Unfortunately, no estimate of precipitation is available for the 1970-71 winter, although it is certain to have been much above the long-term mean. Even though precipitation during the 1971-72 winter was considerably below normal, drifts formed in unprotected cuts, with significant accumulations on the roadway at (unfenced) sites 2, 16, 17, and 20. From Table 8, showing water-equivalent storage at time of peak accumulation at all completed fence systems (related data are given in Appendix F), it is seen that an average of only 10% of the total accumulation at each site was contained in the protected cut.

A critique of each system is given in Appendix G, with recommendations for minor modifications that would maximize system performance.

Table 9 compares actual water-equivalent storage at time of peak accumulation, with that predicted by the design (Eq. 4). As an overall average (but excluding system 14C), total actual storage was 33% greater than predicted by Eq. (4). The primary reason for this discrepancy was that the initial estimate of required capacity did not take into account the precipitation falling between successive rows of fence; that is Eq. (4) was used instead of Eqs. (6) or (7). Using the Cooper Cove System as an example, interfence precipitation would amount to about 30% of total storage. At several sites it is likely that part of the discrepancy was also due to overestimating natural snow storage upwind of the fences. Probable causes for differences between predicted and actual storage for each system (Table 9) are given in Table 10.

Figure 17. Snow accumulation at Site 1 (Cooper Cove) the year before fencing (left; January 16, 1971), compared with conditions near the time of peak accumulation with fences installed (right; February 2, 1972). An aerial view of the system protecting this cut is shown in Figure 2.

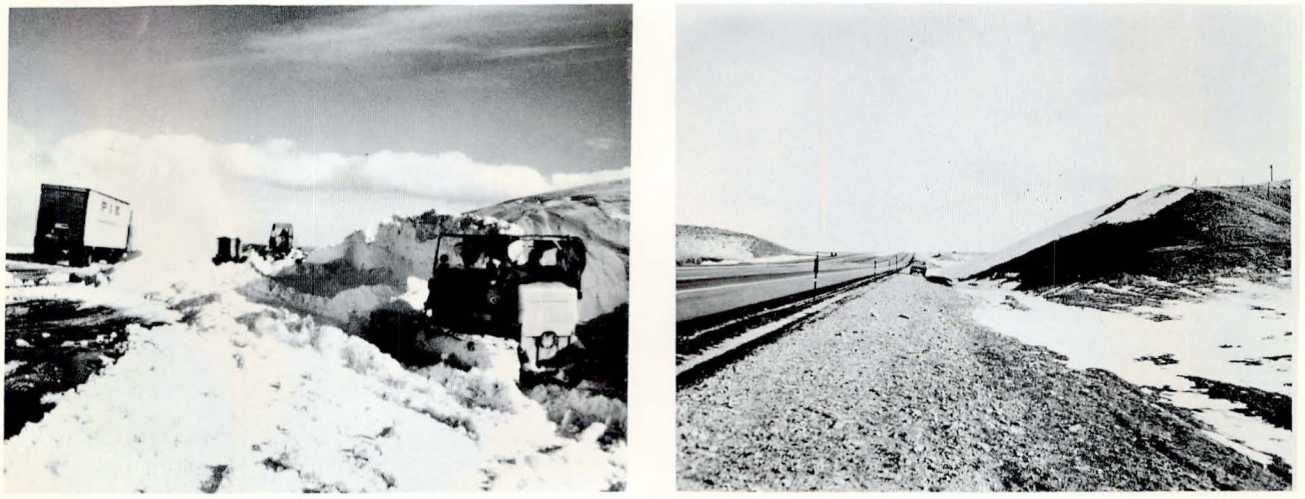


Figure 18. Snow accumulation at Site 4 (Milepost 274.9) the year before fencing (left; March 11, 1971), compared with conditions near the time of peak accumulation with fences installed (right; February 1, 1972).

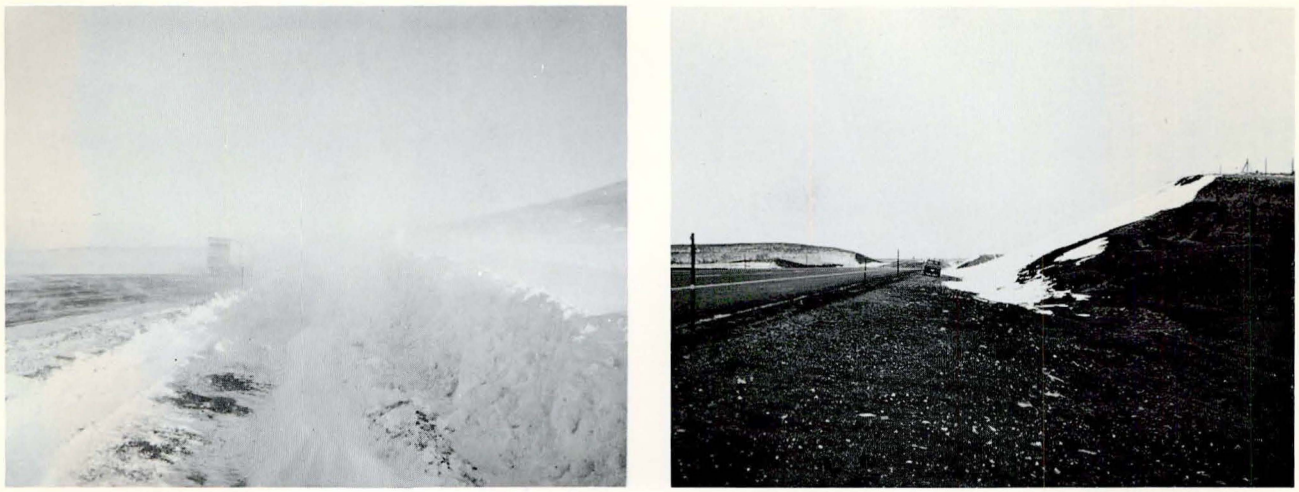


Figure 19. Snow accumulation at Site 5A (Milepost 274.7) the year before fencing (left; March 6, 1971), compared with conditions near the time of peak accumulation with fences installed (right; February 1, 1972).

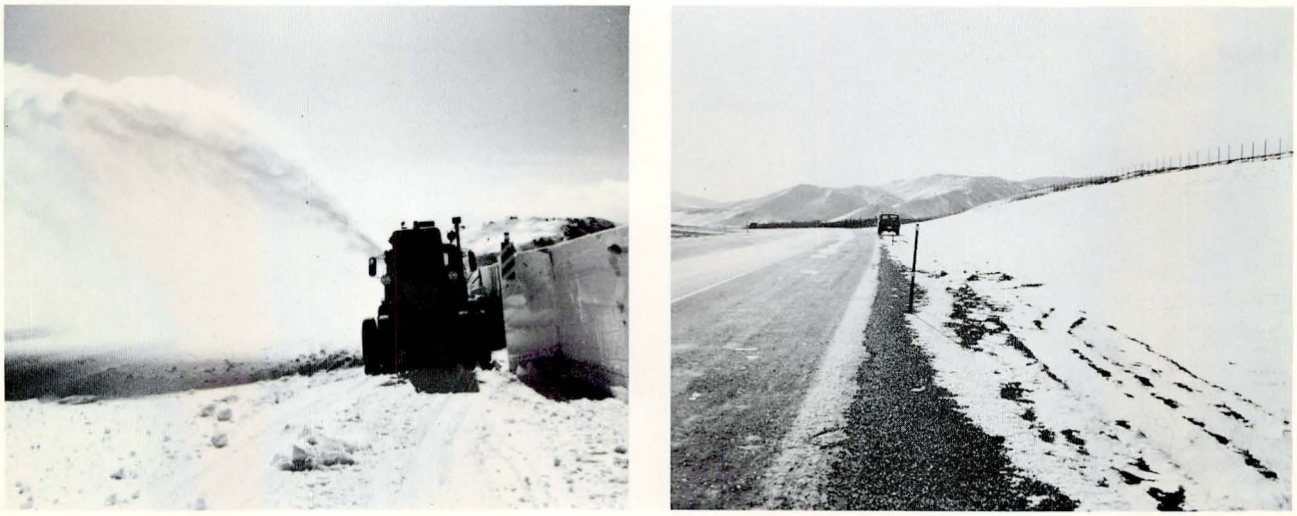


Figure 20. Snow accumulation at Site 9 (Milepost 271.3) the year before fencing (left; March 2, 1971), compared with conditions near the time of peak accumulation with fences installed (right; February 1, 1972).

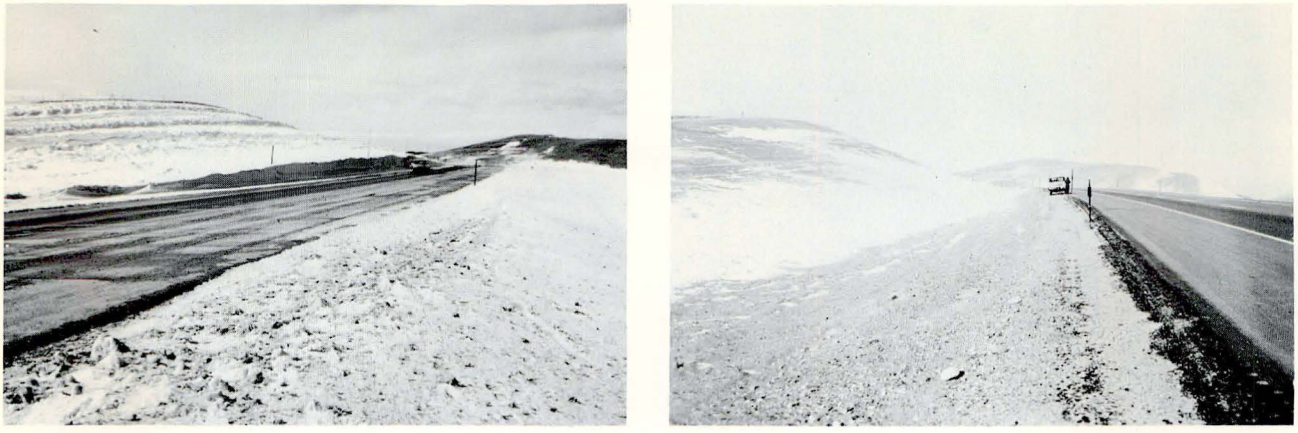


Figure 21. Snow accumulation at Site 12 (Milepost 269.5) the year before fencing (left; February 19, 1971), compared with conditions near the time of peak accumulation with fences installed (right; February 1, 1972). An aerial view of the system protecting this cut is shown below.

Figure 22. Aerial view of System 12 on February 11, 1972. The 12-ft fence in the right foreground is filled to capacity on this date. The main lead fence is 6 ft tall, and the three downwind fences are 12 ft tall. This system is located in the area of highest precipitation, at an elevation of about 7800 ft.

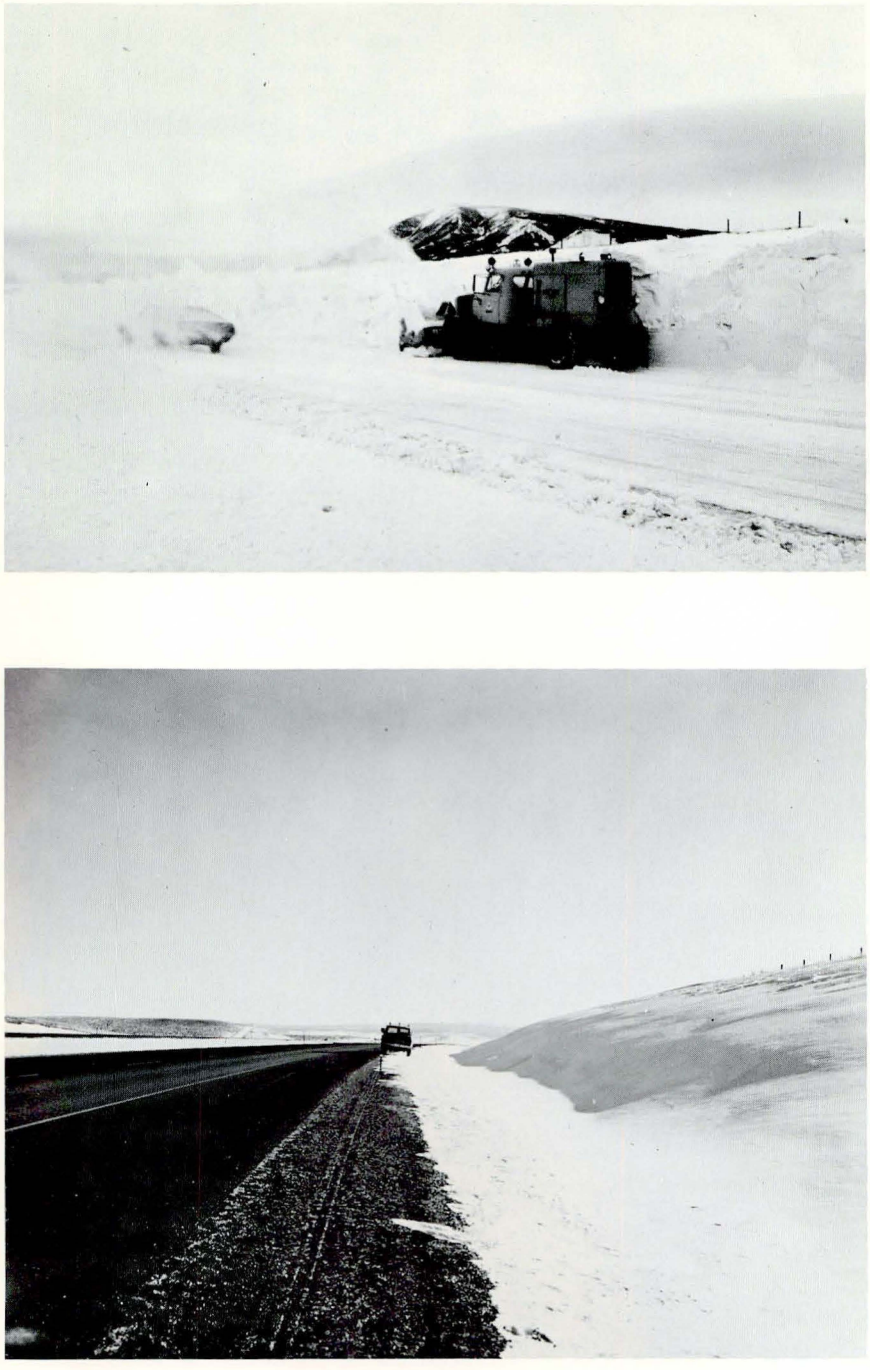


Figure 23. Snow accumulation at Site 23 (Milepost 253.4) the year before fencing (top, January 16, 1971), compared with conditions after the fences were installed (bottom, January 31, 1972).

Table 8. Water-equivalent storage (ft^3/ft) at time of peak accumulation (2/18/72) at all completed fence systems

System number	Milepost	Estimated water-equiv. behind fences at peak	Estimated water-equiv. in cut at peak	Estimated total water-equiv. at peak	Accumulation in cut as % of total
1	280.8	876	27	903	3
4	274.9	816	90	906	10
5A	274.7	885	153	1038	15
5B	274.5	865	70	935	7
5C	274.4	729	94	823	11
6	274.2	1046	40	1086	4
8[a/]	272.1	796	?	796+	?
9	271.3	711	100	811	12
10	270.8	351	96	447	21
11	270.3	563	105	668	16
12	269.5	1481	0	1481	0
14C[b/]	267.2	397	?	397+	?
18	263.5	1105	45	1150	4
19	263.0	1276	178	1454	12
21	261.8	320	102	422	24
22	254.2	1186	109	1295	8
23	253.4	529	118	647	18
Means[c/]		849	88	938	10

a/ System 8 protects Arlington interchange. Snow accumulation within the separation had been removed, so no measurement was possible.

b/ Construction of system 14C (wagonhound interchange) was not completed until late December (?). Actual storage behind the fences was therefore significantly less than that which would have accumulated over the entire season. Accumulation in the cuts and separation was not measured.

c/ Means exclude Systems 8 and 14C.

Table 9 . Comparison of actual water-equivalent storage at time of peak accumulation, with that predicted by the design equation $q_b = 1/2\ (3300)(P-q_s)$, for all completed fence systems.

System number	Milepost	Estimated total precip.[a]	Design q_s[b]	Predicted q_b	Total actual storage at peak
		inches	ft^3/ft	ft^3/ft	ft^3/ft
1	280.8	6.51	0	895	903
4	274.9	7.13	278	702	906
5A	274.7	7.13	94	886	1038
B	274.5	7.13	86	894	935
C	274.4	7.13	107	873	823
6	274.2	7.13	85	895	1086
8	272.1	7.75	0	1066	796+
9	271.3	7.75	498	568	811
10	270.8	7.75	899	167	447
11	270.3	7.75	566	500	668
12	269.5	7.75	236	830	1481
14C[d]	267.2	7.75	400	666	397+
18	263.5	6.86	366	577	1150
19	263.0	6.86	303	640	1454
21	261.8	5.98	362	460	422
22	254.2	5.98	277	545	1295
23	253.4	5.98	197	625	647

[a] Precipitation during accumulation period (10/26 - 3/1/72) only.

[b] Storage by natural vegetation upwind of the fence systems, as estimated during the 1970-71 winter. These are the values used in the original design, as given in last year's report.

[c] Total water-equivalent storage, including accumulation behind the fences and in the protected cuts. Measurements were made at all systems, except 1 and 23, on March 14-16, 1972. The date of peak accumulation, as measured at the two study sites, was February 18. The figures shown are estimates (see Appendix) of peak accumulation, based on the ablation between 2/18 and 3/15 measured at systems 1 and 23.

[d] Construction of system 14C (Wagonhound interchange) was not completed until late December (?). Actual storage is therefore significantly less than that which would have accumulated over the entire winter.

Table 10. Reasons for discrepancies between predicted and actual storage

System number	Reason for difference between predicted actual storage (Table 9)
1	Close agreement
4	Interfence precipitation + overestimate of upwind storage (q_s)
5A	Interfence precipitation
5B	Interfence precipitation
5C	Close agreement
6	Interfence precipitation
8	Not possible to measure actual storage
9	Overestimate of upwind storage (q_s)
10	Overestimate of upwind storage (q_s)
11	Overestimate of upwind storage (q_s)
12	Underestimate of transport distance, + interfence precipitation
18	Unknown, although in part due to interfence precipitation
19	Unknown, although in part due to interfence precipitation
21	Close agreement
22	Unknown, but interfence precipitation and overestimate of upwind storage contributed to discrepancy
23	Close agreement

Anomalous performance of three systems (18, 19, and 22) cannot be explained with any certainty at this time. Because all of these sites are considerably removed from the nearest precipitation gage, an underestimate for precipitation may be responsible for this discrepancy; however, it is entirely possible that the difference is merely the addition of errors arising from interfence precipitation, overestimates of upwind storage, and the initial underestimate of transport distance.

It is concluded that the criteria for spacing (25H on level terrain), arrangement, and topographic placement were adequate as presented in last year's report; however, it is felt that wing fences

should not be used in future designs, since their use is not consistent with the concept of designing systems for adequate capacity. Instead, the main fences should be extended far enough to protect cut-fill transitions against oblique winds.

Fence orientation was judged adequate all sites. In general, orientation is not as critical for well-designed horizontal slat fences as for those constructed of vertical slats, because the effective porosity of horizontal slat fences remains at 50% even though the wind's angle of attack may deviate considerably from the perpendicular. To facilitate proper orientation of future systems, as well as to verify alignment used for the existing fences, wind bearings were determined at half mile intervals from aerial photographs taken on three dates (January 18 and March 19, 1971, and January 7, 1972). Results of this analysis (Fig. 24) should be useful for orienting future fences along I-80.

Capacity and General Performance of the New Standard-Plan Fence.--The new standard-plan fence (Fig. 25) was found to be so effective that its capacity was significantly underestimated in the original design. Figures 26 to 28 show examples of lee drifts as they appeared near the time of peak accumulation. Characteristics of the lee drifts at saturation (Table 11) should be considered as tentative approximations only, because the winter was too short to be certain that lead fences had filled. Indeed, only one fence each of the 10 and 12-ft heights appeared to be full at the time of peak accumulation. Before confidence can be placed on the capacity values given in Table 11, observations must be made during a winter with more snowfall. Table 12 compares original estimates of water-equivalent capacity with actual amounts observed over the 1971-72 winter.

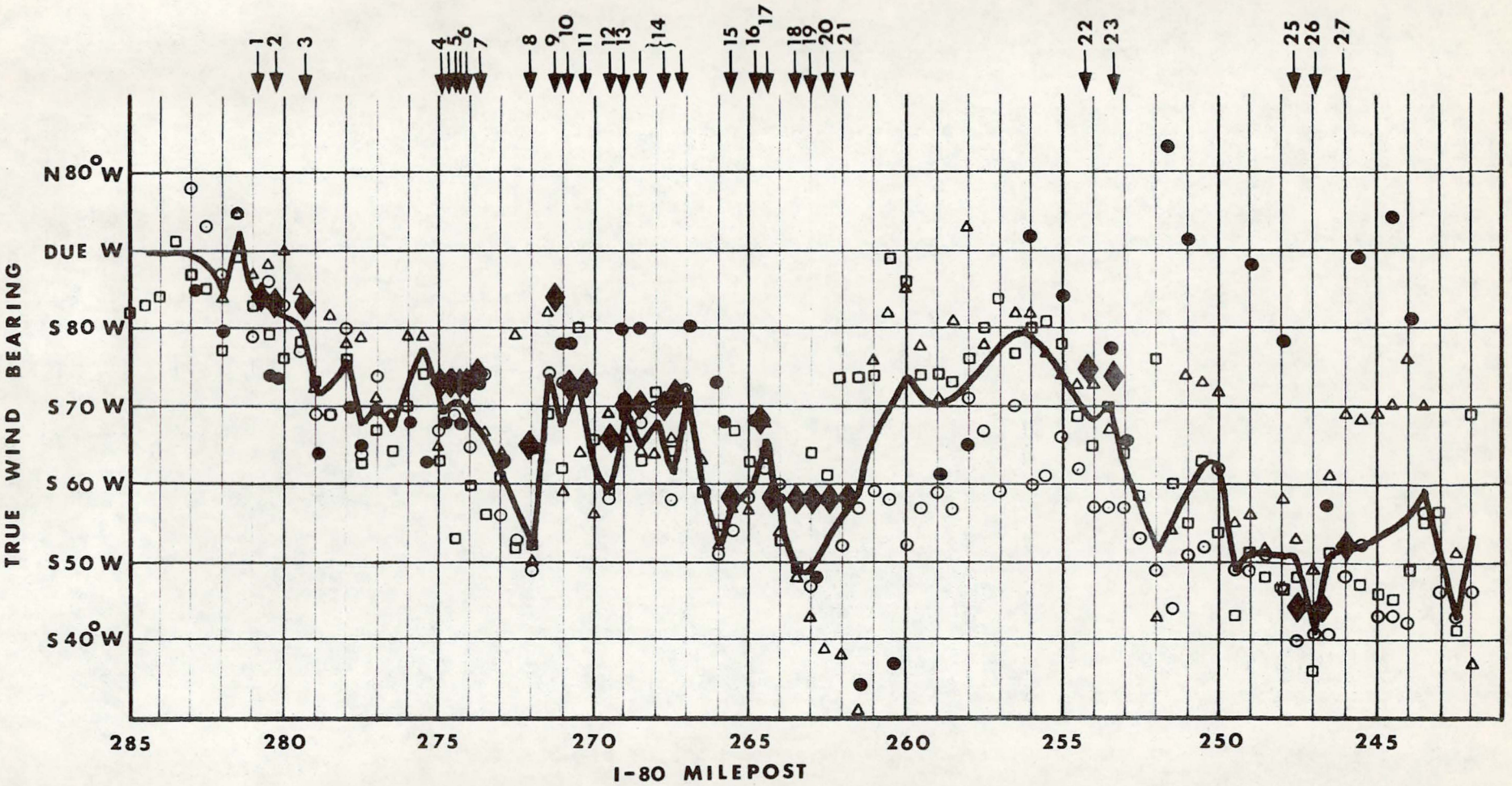


Figure 24. Wind bearings (with respect to true-north) along I-80 as determined from three sets of aerial photographs (January 18, 1971 (○), March 19, 1971 (△), and January 7, 1972 (□), and field measurements on March 7, 1971 (●). The curve drawn through these points represents the direction of the prevailing wind during drifting events, and can be used to orient future fences along the highway. Orientation of fences installed (or under construction) at first-priority sites is shown by (◆).

Figure 25. Typical view of the new standard-plan fence, 12-ft tall. Lead fence at System 22 (Milepost 254.2), February 18, 1972.

Figure 26. Snow accumulation behind lead 12-ft fence at System 22 (Milepost 254.2). Cornice development is typical. January 31, 1972.

Figure 27. Snow accumulation behind 12-ft fence at System 5A (Milepost 274.7). Fence location on ridge increases capacity. Drift is 20 ft deep and contains about 900 ft^3 water-equivalent per lin. ft. February 4, 1972.

Figure 28. Snow accumulation behind 12-ft wing fence at System 12 (Milepost 269.5), near time of peak accumulation (February 16, 1972).

Table 11. Characteristics of drifts behind the new standard-plan snow fence, at saturation (on level terrain).

Factor	Fence height (ft)			
	6	8	10	12
Distance from fence toe to beginning of drift (ft)	6 (1.0H)	6 (0.75H)	10 (1.0H)	13 (1.08H)
Distance from fence toe to end of drift (ft)	156 (26.0H)	167 (20.9H)	200 (20.0H)	230 (19.2H)
Drift length (ft)	150 (25.0H)	161 (20.1H)	190 (19.0H)	217 (18.08H)
Maximum depth (ft)	6.58 (1.1H)	8.83 (1.1H)	11.0 (1.1H)	13.33 (1.11H)
Distance from fence toe to point of maximum depth (ft)	54 (9.0H)	57 (7.1H)	70 (7.0H)	86 (7.17 ft)
Tail slope	1:14.4 (6.9%)	1:11.5 (8.7%)	1:11.25 (8.9%)	1:10.17 (9.8%)
Cross-sectional Area (ft^2)	560	850	1170	1670
Water-equivalent when snow density = 0.5 (ft^3/ft)	280	425	585	835

Table 12. Observed water-equivalent capacity (ft^3/ft) of the Wyoming Highway Department Standard-Plan fence, compared with estimates used in last year's report (Snow density is assumed to be 0.5 g/cm^3)

Fence height	Original estimate (last year's report)	Observed	Observed as % of estimated
6	196	280	143
8	288	425	148
10	388	585	151
12	495	835	169

Cross-sectional area, A (in ft^2), of the lee drifts at saturation can be approximated by

$$A = 34.5\ H^{1.55} \qquad (r = 0.997) \qquad (23)$$

where H is fence height in feet.

In general, capacity of the systems is about 50% greater than planned so that even with the revised capacity requirement given by Eq. (24), there should be sufficient volume to contain all of the blowing snow in 6 or 7 years out of 10 (to be compared with original design for the "average" year. As will be seen from the following section, this implies that the existing systems will be highly efficient in improving visibility.

For future systems along I-80, it appears that two 12-ft fences should be adequate to protect the most severe sites (without significant upwind storage) during an average year. By comparison, the original design called for two 12-ft fences in tandem with an 8-ft fence. Additional study of saturated fences will be required, however before capacity of the new standard-plan fence will be known with certainty.

Effects of Fences on Visibility and Road Surface Conditions.-- Over the 1971-72 winter, forty-eight 100-ft rolls of 16mm movie film documented a dramatic improvement in visibility on the highway downwind of the fences. The greatest improvement was noted during light to moderate drifting. Visibility during heavy drift was noticeably better in locations protected by fences, but there were still periods when visibility was too poor for safe driving. Of course, fences cannot improve visibility during periods of heavy snowfall (precipitation). Figures 29-33 demonstrate the improved visibility behind the fence systems, as recorded by still photographs.

The characteristic that makes snow fences useful for visibility improvement is that fences are efficient in trapping blowing snow even when they are more than 75% full (as will be shown in the next section). Dramatic visual evidence of this is shown in the aerial view of Figure 29, which was taken when the fence system contained about 75% of its capacity.

In general, less slush and ice forms on road surfaces downwind of fences than in unprotected areas (Fig. 34 and 35), due primarily to the reduced amount of snow blowing across the road. This beneficial effect occurs only when the road surface is warmer than the air/snow temperature. On some occassions after a snowstorm with light

Figure 29. Very little blowing snow is seen escaping the dual 12-ft fences at System 19. At the time this picture was taken (February 11, 1972, 1645 MST), this system was about 75% full, containing more than 1200 ft^3 of water-equivalent per lineal ft.

Figure 30. In this view from behind System 19, the abrupt transition in visibility conditions appears as a wall of blowing snow at the end of the fences (February 16, 1972).

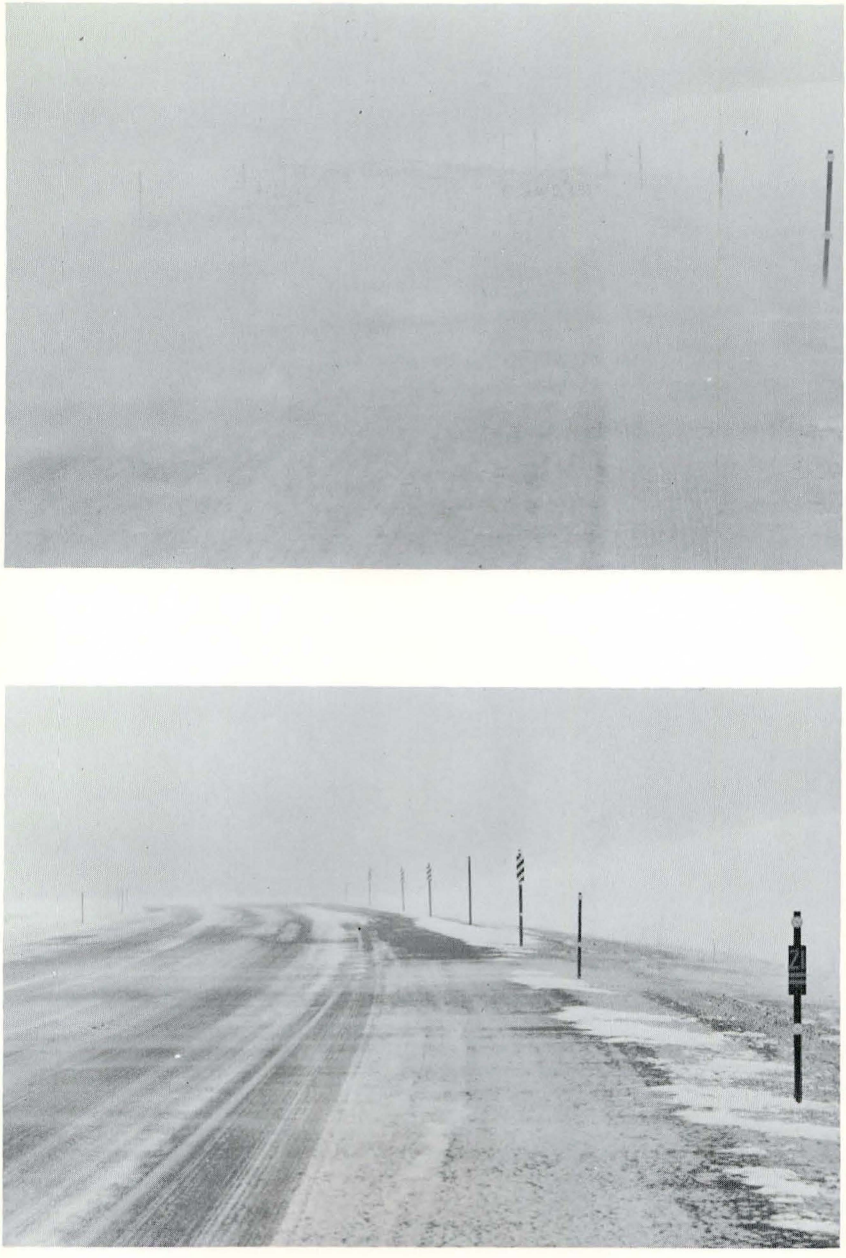


Figure 31. These two views demonstrate the dramatic improvement in visibility downwind of the fence systems during moderate drifting. The top view was taken 200 ft outside of the protection of System 21 (Milepost 262), east-bound lane. The bottom view was taken a few minutes later, standing at the protection boundary (marked by the signpost "21"). Visibility improvement behind fences was observed to a greater or less degree during all drifting events, and was documented in more than forty separate rolls of 16-mm movie film. These pictures were taken late in the afternoon on February 15, 1972, while the road was closed to traffic (Wyoming Highway Department Photo).

Figure 32. Reduction of low-level drift downwind of systems 18 and 19 (milepost 263-264) is clearly visible in this view down the east-bound lane. The area protected by the fence system (19) on the right begins at the fourth delineator post. Snow passing through the gap between the two systems can be seen as a white band across the protected area. (January 14, 1972, 1345-1400 MST).

Figure 33. Effect of fences on visibility during light drift can be clearly seen in this view behind System 22 (milepost 254). The picture was taken from the top of the cut, centered downwind of the fences. The south end of the protection area coincides with the end of the cut, just beyond the mileage sign on the east-bound lane. Note the abrupt transition between conditions. January 4, 1972, 1225 MST.

Figure 34. Transition of road surface conditions entering and leaving protection of fences. (Top) The frozen slush-covered road is outside fence protection. Boundary between wet (dark) pavement and frozen slush in foreground coincides exactly with the beginning of the fence system (the fence system boundary marker can be seen on the first delineator post in front of the truck). System 22 (milepost 254), west-bound lane, on February 16, 1972.

(Bottom) Abrupt transition in road conditions on other end of System 22, same date as above. Next delineator post behind that with the milepost marker holds the fence boundary marker.

Figure 35. The change from frozen slush in the foreground, to wet road in the background, coincides with the protection boundary at System 4 (milepost 274.9, west-bound lane). February 15, 1972; 1120 MST.

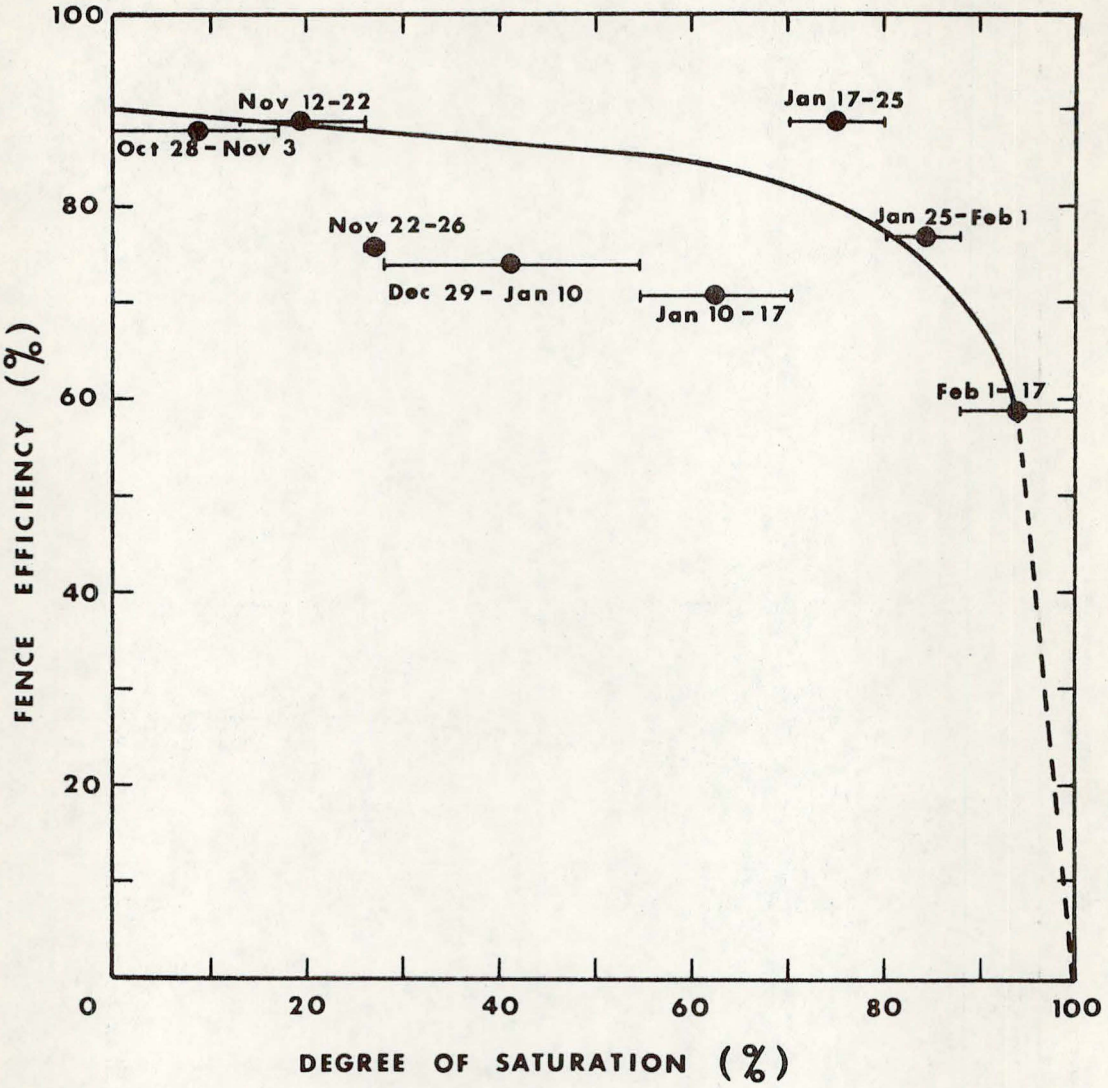


Figure 36. Efficiency of the lead 8-ft fence at Cooper Cove as a function of degree of saturation. Efficiency is defined as the proportion of incoming snow trapped by the fence, expressed in percent, as calculated from Eq. (12). Degree of saturation is the amount of snow contained in the lee drift, expressed in percent of maximum storage when the fence is full.

wind, more snowpack was observed on the road in fenced cuts than in unprotected areas. This occurs when windspeeds in the protected stretches are slightly below those needed to sweep the snow off the highway, and when the road surface temperature is at, or below, the air/snow temperature. Because this negative effect is relatively infrequent, and because snowpacked roads constitute less driving hazard than slush and ice, it is concluded that the overall effect of fences on road surface conditions is beneficial.

To the author's knowledge, the above effects of fences on visibility and road surface conditions have not been previously reported in the literature. These beneficial effects are realized behind the I-80 fences because the tall (12 ft) barriers remove a large percentage of the total drift, and because the capacity of the systems is sufficient to maintain trapping efficiency throughout the winter.

Fence Efficiency.--The efficiency of a lead 8-ft fence (at the Cooper Cove study site) was determined for each measurement period using Eq. (12), and was expressed as a function of degree of saturation. Although more data will be required to accurately define this curve, data from the 1971-72 winter strongly suggest a convex relationship (Fig. 36). An average curve, fitted by eye, shows efficiency to decrease very slowly as a fence fills, with nearly 80% of the incoming snow still being trapped by the time the fence is 75% full. Average efficiency of the fence, from onset of accumulation to time of saturation, is about 80%. The functional form of this relationship is confirmed by observations that fences continued to improve visibility and prevent snow accumulation in protected cuts throughout the entire winter.

CONCLUSIONS AND RECOMMENDATIONS

1. The existing fence systems along I-80 should provide adequate protection 6 or 7 years out of 10, and no major modifications are required. Minor adjustments that would maximize system performance are given in Appendix G, and have been discussed with the District Engineer.

2. The basic approach used to estimate required capacity of the fence systems is valid. Refinements made possible by this study are given in Recommendation 7.

3. Standardizing fence heights at 8 and 12 ft should improve the economy of future construction. Based on cost per unit volume of storage, 12-ft fences are the most economical.

4. After two years' experience with blowing snow conditions on I-80, the author concludes that an adequate snow control system would make snow removal operations along I-80 comparable with those required on the original U.S. 30 route; indeed, this objective will nearly be met once the remainder of the first-priority fences are installed. Winter driving conditions (visibility and ice) are also greatly improved downwind of the existing systems, but it is estimated that nearly 100,000 ft of additional fencing would be required to attain an acceptable degree of protection along the entire road between mileposts 240 and 290. Although the utility of fences is now beyond question, they cannot be expected to eliminate all of the hazards. In view of the importance of I-80, and the rigorous winter conditions, consideration should be given to a traffic control scheme incorporating a condition monitoring system that could eventually be expanded to include condition prediction.

5. Systems employing 12-ft fences, and designed for adequate capacity, can be used to improve visibility and reduce ice and slush formation on the road surface. However, a definite hazard exists in the sudden transition from protected to unprotected roadway (see Figs. 30, 33, and 34). For example, a visual range of 1000 ft behind a fence system may deteriorate to 100 ft or less within a distance of 50 ft after leaving the fence protection. An emphatic recommendation is that fence protection be gradually decreased at the end of a system, or tied into some natural feature that eliminates an abrupt transition.

6. Additional study should be made of the storage capacity of the new standard-plan fence during a winter with more precipitation. The values from this study (Table 11) must be considered as tentative approximations only. The new design is exceptionally efficient and should be adopted as a standard.

7. Although there is good reason to question the practice of designing snow control systems for the <u>average</u> year, an economic assessment of the problem must probably await more experience. It is important to realize, however, that under this criterion the relationship between fence efficiency and degree of saturation (Fig. 36) implies that during a winter with average precipitation, about 20% of the blowing snow arriving at a site will pass through the fence system and be deposited in the protected cut. This may not be acceptable in cuts with limited capacity, or where visibility improvement is desired.

8. Although the original method for estimating the required capacity of fence systems proved to yield reasonable values, results from this study permit a more rigorous approach that should be less

vulnerable to the possibility of non-compensating errors. Under the criterion of providing 80% protection during a winter with average precipitation, the required capacity of future fence systems should be estimated from

$$\bar{q}_t \doteq (1 - \bar{a}) \left\{ (1/2)\bar{\theta}\bar{P} \left[2\bar{R}_m - (R_c^2 / R_m) + 2r_1 + \cdots + 2r_i \right] \right\} \qquad (24)$$

where $\bar{q}_t$ = required water-equivalent capacity of the snow fence system during an average year, in ft^3 per lin. ft of fence

$\bar{a}$ = average net ablation over the accumulation season, expressed as a fraction of gross accumulation (approximately = 0.10)

$\bar{\theta}$ = mean annual snow transfer coefficient, with the following approximate values:

Vegetation + terrain conditions	$\bar{\theta}$
Smooth grassland	0.9
Low-growing brush (4-8" tall)	0.8
Intermediate brush (8-16"), or small topographic traps	0.7
Tall brush (> 16"), or moderate topographic traps	0.6

$\bar{P}$ = mean winter precipitation (ft)

$$= (1/12) \left[6.9 + 0.005 \text{ (Elevation - 7275)} \right]$$

$\bar{R}_m$ = mean distance of snow transport (ft), with the following approximate values:

Elevation (ft)	R_m (ft)
7200 - 7400	3300
7400 - 7600	3900
7600 - 7800	4500
>7800	5100

R_c = mean distance upwind contributing blowing snow at a site (but never greater than R_m), in ft

r_i = distance between successive rows of fences in a series (ft); approximately equal to 25H, where H is total fence height (ft)

Equation (24) must be solved by trial and error, beginning with an estimate for the number of rows of fencing required at a site. For example, for a site at 7700 ft with shortgrass vegetation and no upwind barriers to snow movement ($R_c = R_m$), and starting with the estimate that two rows of 12-ft fence will be required,

$$\bar{q}_t = (1 - 0.1)\left\{(1/2)(0.9)(0.75)\left[2(4500) - \frac{(4500)^2}{4500} + 2(25)(12)\right]\right\}$$
$$= 1549 \text{ ft}^3 \text{ water-equivalent per lin. ft.}$$

From Table 11, two rows of 12-ft fence would contain approximately 1670 ft^3/ft, or about 200 ft^3 more than that estimated to be available. Therefore, the system would be adequate to contain the amount of snow anticipated at the site during an average year.

It is interesting to compare this result with the amount of protection required at a 7300-ft site with intermediate-height brush. Again assuming $R_c = R_m$, Eq. (24) indicates that a single row of 12-ft fence would be adequate to contain the anticipated amount of blowing snow (609 ft^3 water-equivalent per ft).

9. In locations where visibility improvement is the prime objective, fence systems should intentionally be overdesigned with respect to required capacity, in order to maintain efficiency near the 90% level over the average winter.

10. Although this study did not have as an objective the identification of new sites requiring protection, the author is acutely aware of the need for snow fencing to improve visibility between mileposts 275.5 and 278. This stretch of road was the scene of several multiple-vehicle accidents over the 1971-72 winter, including an awesome 11-vehicle affair on St. Valentine's Day (milepost 277). The author designed and surveyed a fence system for this portion of highway (Fig. 37), and field notes have been given to the District Engineer. It is recommended that this system be given highest priority for future construction.

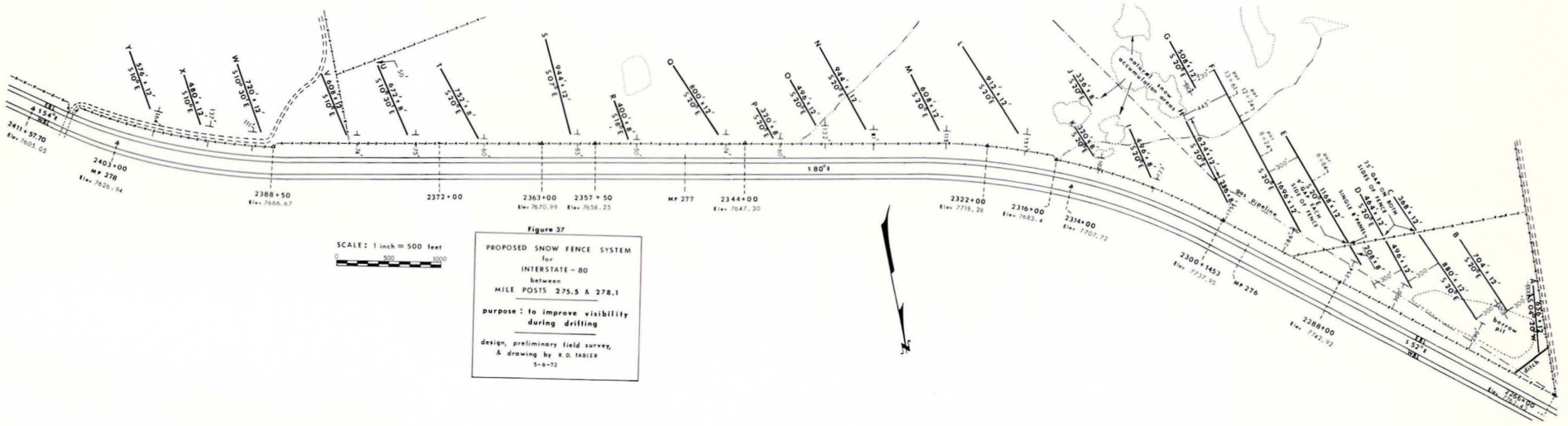


Figure 37. Fence system proposed to improve visibility between Mileposts 275.5 to 278.0.

LITERATURE CITED

Mellor, Malcolm. 1965. Blowing Snow. Cold Regions Res. and Eng. Lab., Cold Regions Sci. and Eng. Part III, Sect. A3c. 79 p.

Schmidt, R. A. Jr. 1972. Sublimation of wind-transported snow--a model. USDA Forest Service Research Paper, RM-90. 24 p.

Tabler, Ronald D. 1971a. Design of a watershed snow fence system, and first-year snow accumulation. West. Snow Conf. (Billings, Mont., April, 1971) Proc. 39:50-55.

_____. 1971b. Recommended snow control measures for first-priority sites on I-80 between Laramie and Walcott, Wyoming. Final report on Contract No. 16-225 with the Wyoming Highway Department. 73 p.

_____ and Robert L. Jairell. 1971. A recording gage for blowing snow. USDA Forest Service Research Note RM-193. 7 p.

_____ and R. A. Schmidt. 1972. Weather conditions that determine snow transport distances at a site in Wyoming. Accepted for presentation at the International Hydrology Symposium on the Role of Snow and Ice in Hydrology, to be held September 6-14, 1972, at Banff, Alberta, Canada.

APPENDIX

A. Instrument location maps

B. Snow accumulation data at the intensive study sites

C. Residual snow upwind of the intensive study sites

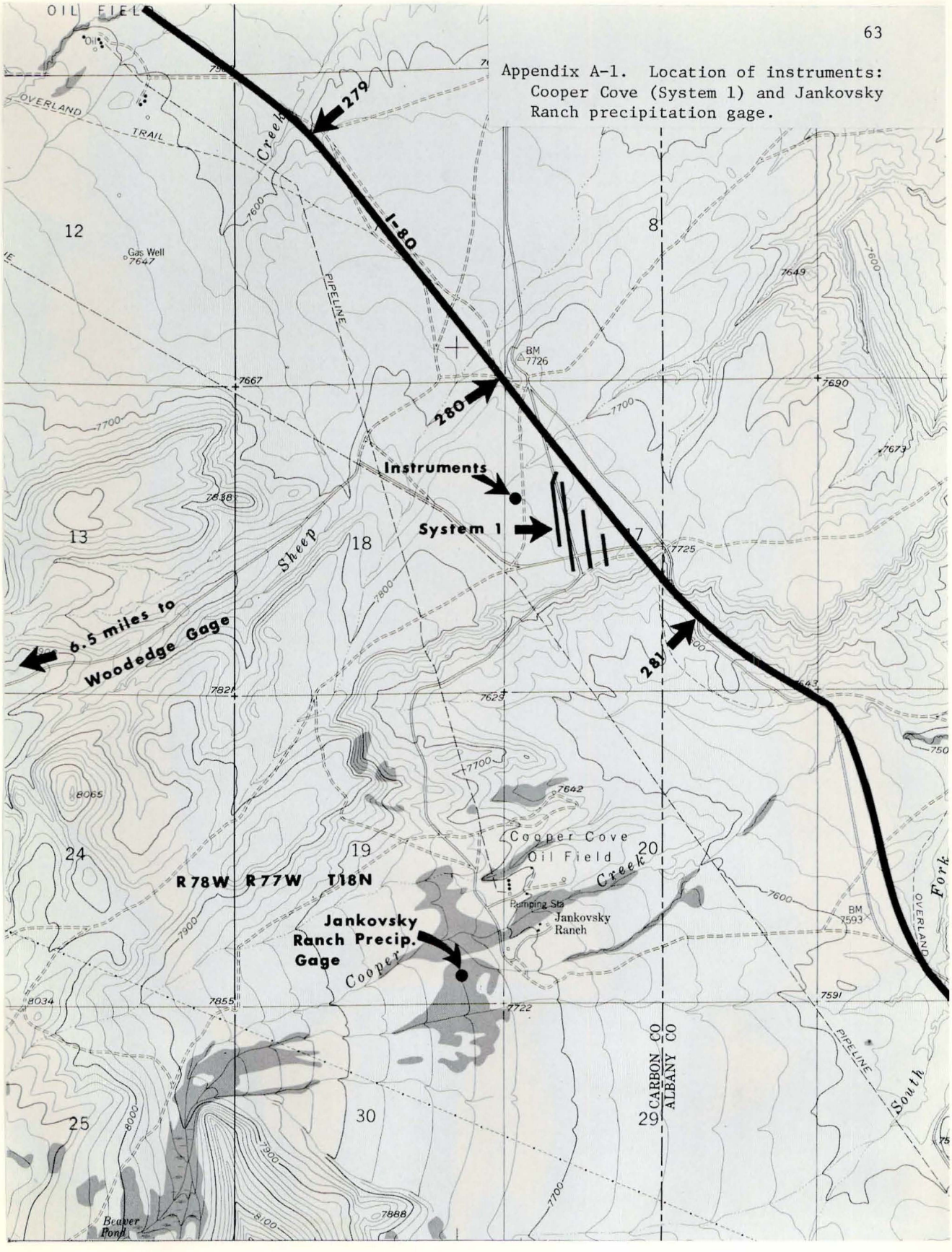
D. Snow accumulation, mass transport, and weather conditions, during drifting at the intensive study sites

E. Precipitation data

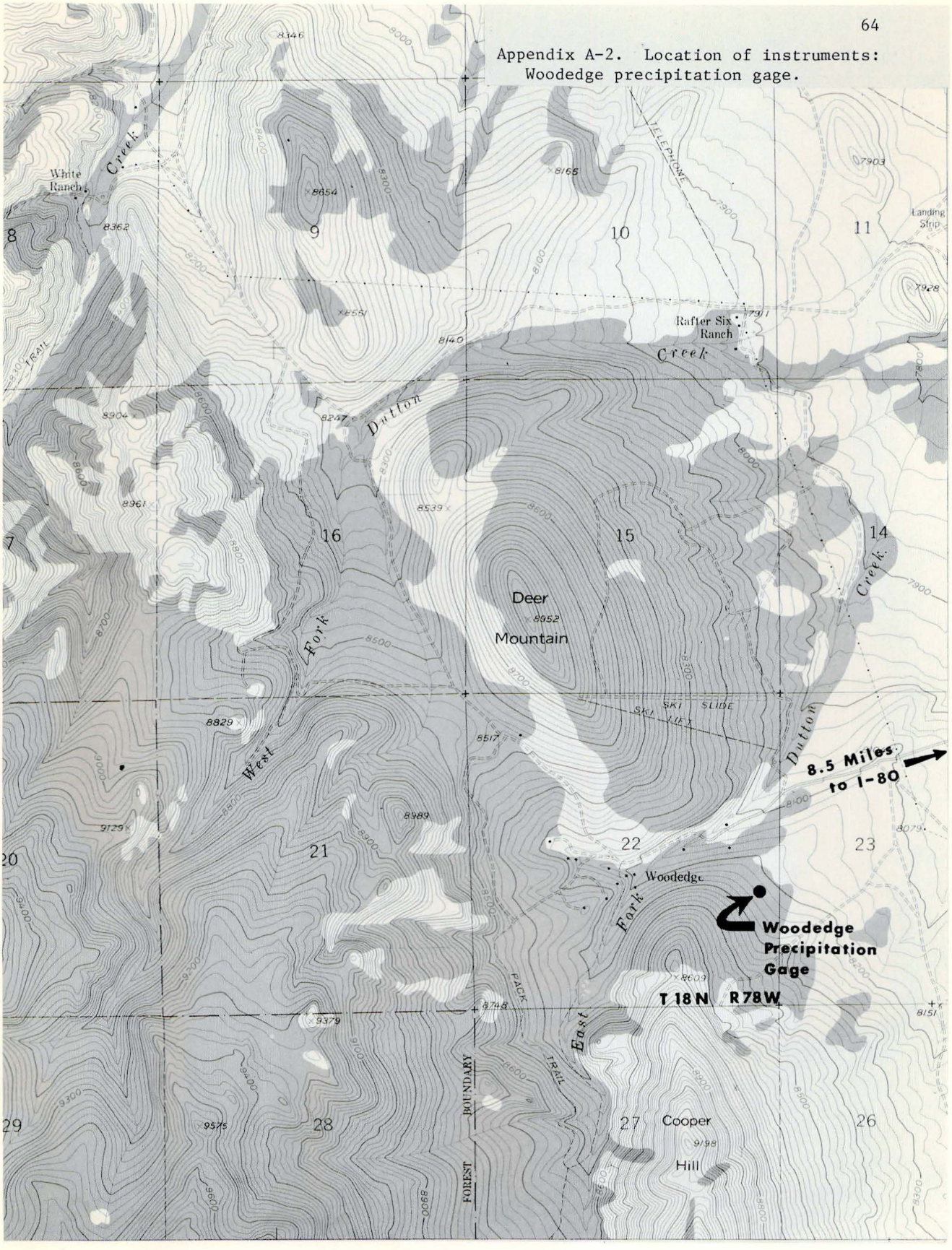
F. Water-equivalent storage data for all completed fence systems

G. Critique of existing fence systems, and recommendations for modifications to maximize performance

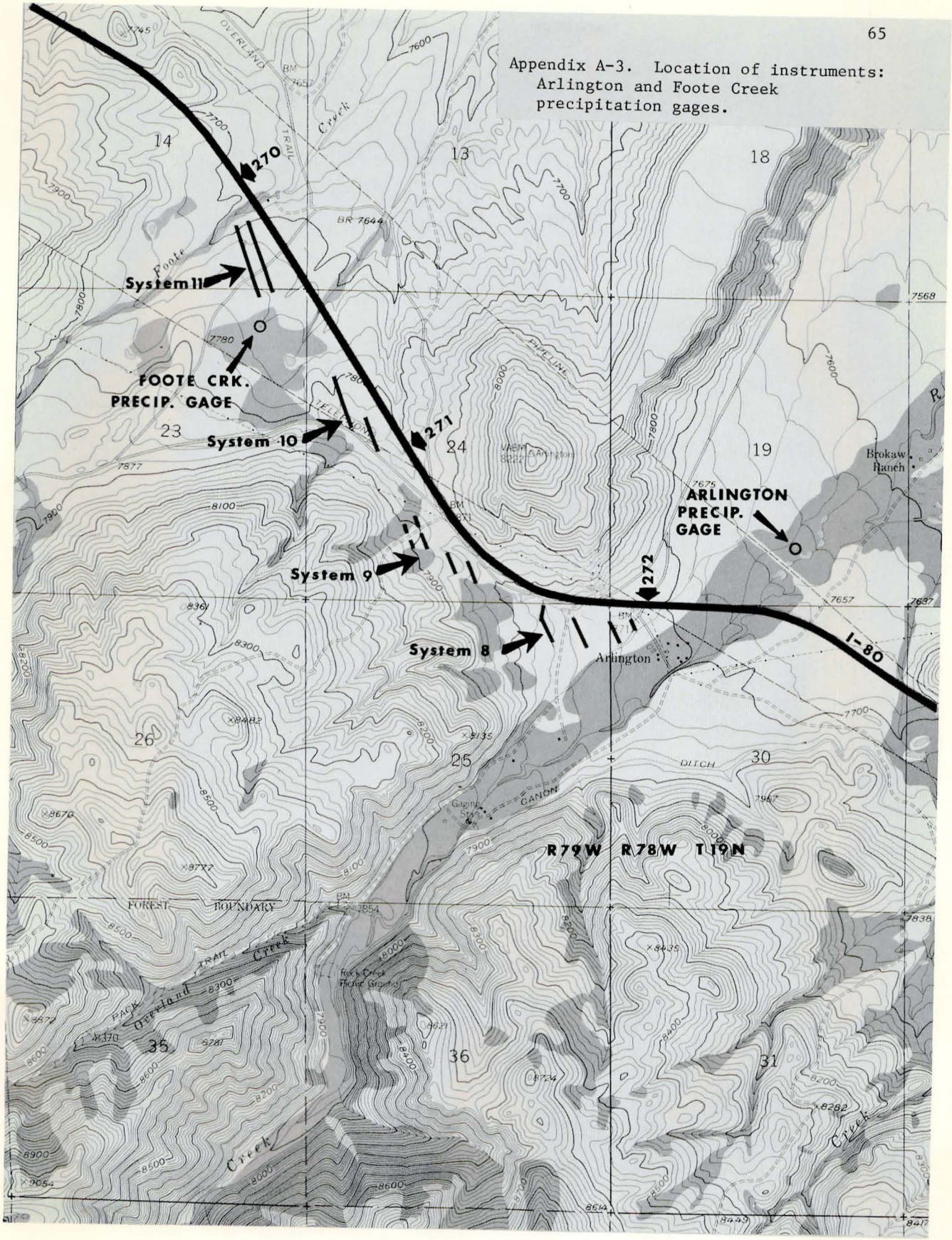
Appendix A-1. Location of instruments: Cooper Cove (System 1) and Jankovsky Ranch precipitation gage.



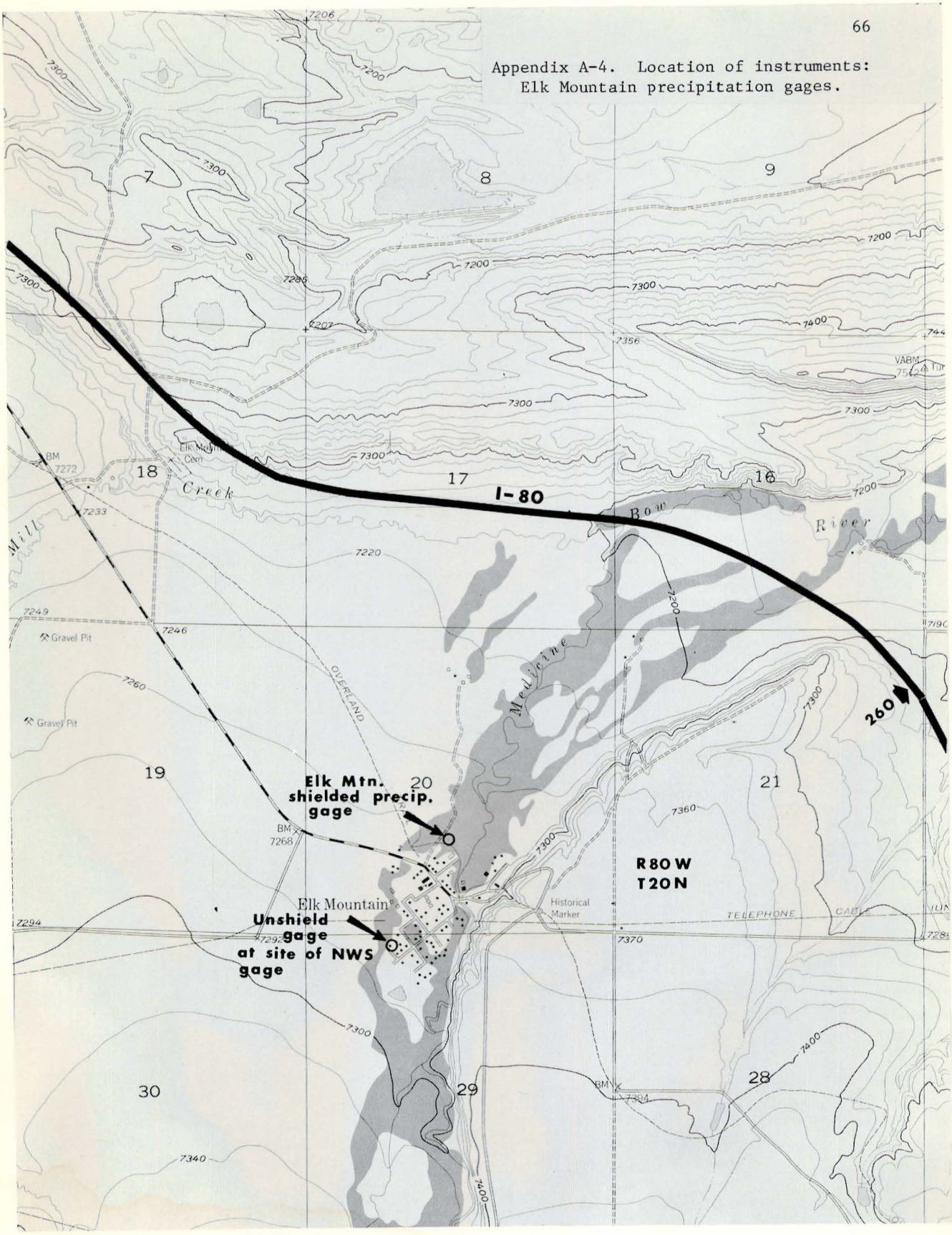
Appendix A-2. Location of instruments: Woodedge precipitation gage.

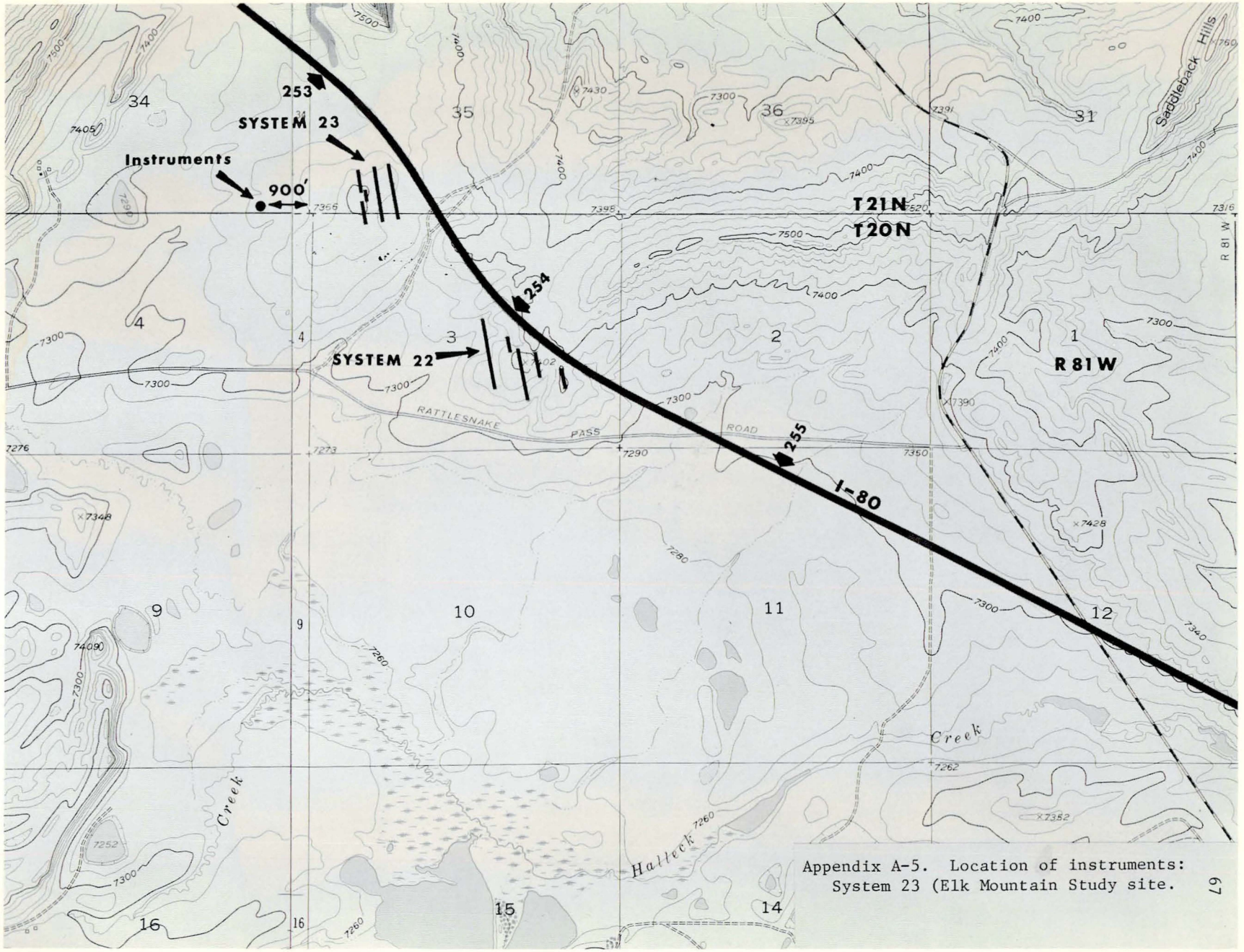


Appendix A-3. Location of instruments: Arlington and Foote Creek precipitation gages.



Appendix A-4. Location of instruments: Elk Mountain precipitation gages.





Appendix A-5. Location of instruments: System 23 (Elk Mountain Study site.

Table B-1. Snow storage at the Cooper Cove Study Site (System 1) over the 1971-72 winter. Each value is the average of four transects. Fence 1 is the lead fence and is 8 feet tall; fences 2 and 3 are 12 feet tall.

Date	Cross-sectional Areas of Drifts (ft^2)				Water-Equivalent of Drifts (ft^3/ft)				
	Fence No.				Fence No.				
	1 (upwind)	1 (lee)	2	3	1 (upwind)	1 (lee)	2	3	Total
11-3-71	69.8	168.6	60.8	47.7	29.6	71.5	25.8	20.2	147.1
11-12-71	43.3	124.3	29.5	9.4	21.1	60.8	14.4	4.6	100.9
11-22-71	33.5	254.5	64.1	24.0	16.4	129.0	27.8	10.4	183.6
11-26-71	33.5	273.3	78.7	34.7	16.4	133.1	31.0	12.7	193.2
12-2-71	29.6	271.9	73.5	36.3	14.8	137.3	31.3	15.5	198.9
12-14-71	26.3	286.8	92.6	43.7	13.2	139.9	42.3	20.0	215.4
12-29-71	0	274.4	72.2	29.0	0	138.3	35.7	12.0	186.0
1-10-72	69.5	535.0	211.1	93.8	29.0	270.3	96.3	37.5	433.1
1-17-72	65.1	688.3	304.5	123.5	27.9	333.4	131.9	46.2	539.4
1-25-72	61.3	786.9	366.7	148.8	27.0	360.6	143.7	55.5	586.8
2-1-72	78.1	861.6	402.6	178.1	30.9	403.1	163.1	65.6	662.7
2-17-72	85.8	980.2	506.6	244.8	33.9	477.2	230.8	100.6	842.5
2-24-72	69.2	928.2	479.6	215.7	33.2	477.3	232.5	93.1	836.1
3-3-72	50.6	887.7	494.5	202.6	27.7	468.1	244.6	93.8	834.2
3-10-72	18.2	766.5	417.2	136.8	10.9	417.4	219.8	73.3	721.4
3-16-72	0	624.7	335.9	93.6	0	363.1	180.0	50.2	593.3
3-30-72	0	438.5	225.6	21.6	0	250.8	109.6	10.3	370.7
5-1-72	0	0	0	0	0	0	0	0	0

Table B-2. Snow storage at the Elk Mountain study site (System #23) over the 1971-72 winter. Each value is the mean of three transects. Fence number 1 is the lead (farthest upwind) fence and is 8 feet tall. Fences 2 and 3 are 10 and 12 feet tall, respectively.

Date	Cross-sectional Area of Drifts (ft^2)			Water-Equivalent of Drifts (ft^3/ft)			
	Fence Number			Fence Number			
	1	2	3	1	2	3	Total
11-2-71	221.6	79.1	80.7	87.3	31.2	31.8	150.3
11-11-71	130.1	21.8	26.8	62.2	10.4	12.8	85.4
11-23-71	170.8	36.0	32.6	76.8	14.6	13.2	104.6
11-26-71	170.8	36.0	32.6	76.8	14.6	13.2	104.6
12-3-71	249.2	58.0	51.9	102.3	20.1	18.0	140.4
12-13-71	498.1	134.0	116.1	215.7	47.4	37.5	300.6
12-28-71	480.1	121.0	95.1	240.0	53.9	41.8	335.7
1-7-72	558.7	192.0	133.5	263.5	81.3	50.2	395.0
1-17-72	560.3	177.5	120.0	282.3	75.6	47.7	405.6
1-26-72	554.9	168.7	116.2	272.8	69.9	44.3	387.0
1-31-72	608.6	200.0	136.5	303.8	87.2	48.1	439.1
2-18-72	773.1	274.6	171.8	355.7	110.2	63.4	529.3
2-24-72	661.8	213.0	139.7	331.6	94.7	65.3	491.6
3-3-72	612.9	202.6	119.1	321.8	97.9	53.1	472.8
3-9-72	492.7	130.3	59.5	289.9	68.7	30.1	388.7
3-16-72	314.8	54.8	0	179.9	29.1	0	209.0
4-10-72	0	0	0	0	0	0	0

Table C-1. Snow water-equivalent (inches) remaining upwind of the fences at the two study sites on all measurement dates during the accumulation season.

Cooper Cove (System 1)				Elk Mountain (System 23)			
Date	w.e.	initial w.e.	Δw.e.	Date	w.e.	initial w.e.	Δw.e.
11-3-71	?	0	?	11-3-71	0.60	0	0.60
11-19-71	0.19	0	0.14	11-11-71	0	0.60	-0.60
11-26-71	0.046	0	0.046	11-19-71	0.40	0	0.40
12-2-71	0.069	0.046	0.023	11-26-71	0.166	0.40	-0.234
12-14-71	0.022	0.022	0	12-3-71	1.074	0.166	0.908
12-29-71	0.024	0	0.024	12-13-71	1.12	1.07	0.05
1-7-72	0.058	0	0.058	12-28-71	0.38	0.23	0.15
1-17-72	0.04	0	0.04	1-7-72	0.37	0.10	0.27
1-25-72	0.0395	0	0.040	1-17-72	0.376	0.37	0
2-1-72	0.04	0	0.04	1-26-72	0.134	0.37	-0.236
2-17-72	0.07	0	0.07	1-31-72	0.56	0.134	0.426
				2-18-72	0.52	0.56	-0.04

Table D-1. Snow accumulation, mass transport, and mean (weighted) weather conditions during drifting at the Cooper Cove (system 1) study site for all sampling intervals during the accumulation season.

Period	Change in water-equiv, storage behind fences	Mass transport at 0.5 meter height[a/]	Wind speed[b/]	Wind Azimuth[b/]	Relative Humidity[c/]	Air Temp.[c/]	Solar rdn.[b/]
	$m^3 \cdot m^{-1}$	$g \cdot cm^{-2}$	$m \cdot sec^{-1}$	deg.	%	°C	$cal \cdot cm^{-2} hr^{-1}$
10/27 - 10/29/71	13.67	31	11.9	150	90	-9.4	11.7
10/30 - 11/3		389	17.7	255	74	-11.3	38.8
11/3 - 11/12	-4.29	0	----	---	--	-----	----
11/12 - 11/22	7.68	163	19.2	248	76	-9.0	3.3
11/22 - 11/26	0.89	13	12.4	278	76	-5.4	0.1
11/26 - 12/2	0.53	0	----	---	--	-----	----
12/2 - 12/14	1.53	26	13.7	256	75	-3.6	22.1
12/14 - 12/29	-2.73	9	14.2	263	73	-6.6	0
12/29 - 1/10/72	22.96	610	17.9	259	85	-8.5	6.1
1/10 - 1/17	9.88	230	14.8	268	81	-11.9	18.5
1/17 - 1/25	4.40	240	13.5	263	77	-8.3	24.5
1/25 - 2/1	7.05	82	13.5	266	80	-12.7	4.8
2/1 - 2/17	16.71	293	15.1	270	82	-4.9	9.3

[a/] Mass flux was sampled by the recording, rotating drift gage. Intake orifice area = 3.12 cm^2

[b/] Instruments installed at 2-meter height above the ground

[c/] Instruments installed at 1.5-meter height above the ground

Table D-2. Snow accumulation, mass transport, and mean (weighted) weather conditions during drifting at the Elk Mountain (System 23) study site for all sampling intervals during the accumulation season.

Period	Change in water-equiv, storage behind fences	Mass transport at 0.5 meter height[a/]	Wind speed[b/]	Wind Azimuth[b/]	Relative Humidity[c/]	Air Temp.[c/]	Solar rdn.[b/]
	$m^3 \cdot m^{-1}$	$g \cdot cm^{-2}$	$m \cdot sec^{-1}$	deg.	%	°C	$cal \cdot cm^{-2} hr^{-1}$
10/27 - 10/29	13.96	233	11.9	86	?	-9.4	11.7
10/29 - 11/2		198	15.8	246	?	-10.1	33.8
11/2 - 11/11	6.03	0	----	---	--	----	----
11/11 - 11/23	1.78	5	?	?	?	?	0
11/23 - 11/26	0	0	----	----	--	----	----
11/26 - 12/3	3.33	6	9.4	250	82	-3.3	26.5
12/3 - 12/13	14.88	67	13.3	241	78	-8.5	8.4
12/13 - 12/28	3.26	23	12.0	237	85	-8.2	2.4
12/28 - 1/7	5.51	49	13.8	245	77	-10.4	15.2
1/7 - 1/17	0.98	1	13.3	260	75	-12.7	44.6
1/17 - 1/26	1.73	2	10.3	255	79	-4.6	11.9
1/26 - 1/31	4.84	4	10.0	249	82	-11.3	21.1
1/31 - 2/18	8.38	95	13.1	242	95	-2.4	9.3

[a/] Mass flux was sampled by the recording, rotating drift gage; intake orifice area = 3.12 cm^2.

[b/] Instruments installed at 2-meter height above the ground.

[c/] Instruments installed at 1.5-meter height above the ground.

Table E-1. Daily precipitation amounts (inches) as measured by the recording precipitation gages (RRG).

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
September (1971)	16	0.27	0.19	0.13	----	0.20
	17	0.74	0.60	0.23	----	0.52
	18	0.04	0	0	----	0.01
	20	0.43	0.27	0.08	----	0.26
	21	0.24	0.19	0.15	----	0.19
	28	0	0.02	0.03	0	0.02
October	1	0.06	0.05	0	0	0.04
	2	0	0.07	0.15	0.10	0.07
	10	0.03	0	0	0	0.01
	16	0	0	0.01	0.01	0
	17	0.10	0.18	0.06	0.04	0.11
	18	0.02	0.14	0.07	0.06	0.08
	21	0.01	0	0	0	0
		----------Snow accumulation began behind the fences----------				
	26	0	0	0.02	0.02	0.01
	27	0.26	0.58	0.51	0.47	0.45
	28	0.39	0.33	0.52	0.30	0.41
	29	0.18	0.05	0.05	0.03	0.09
	30	0.07	0.07	0.06	0.06	0.07

Table E-1. (con't)

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
November	1	0.03	0.04	0	0	0.02
	2	0.05	0	0	0	0.02
	5	0.02	0	0	0	0.01
	15	0.04	0.11	0.16	0.13	0.10
	16	0.23	0.34	0.15	0.13	0.24
	17	0.10	0.15	0.16	0.16	0.14
	18	0	0.02	0.01	0	0.01
	19	0.04	0	0	0	0.01
	23	0.01	0.04	0.06	0.03	0.04
	25	0.14	0.12	0.08	0.05	0.11
	27	0.08	0.15	0.15	0.11	0.13
	28	0.01	0.13	0.06	0.04	0.07
	29	0.01	0.13	0.08	0.03	0.07
	30	0.05	0.03	0.03	0.05	0.04
December	1	0.01	0.005	0.01	0.01	0.01
	2	0	0.005	0.02	0.01	0.01
	3	0	0.02	0.02	0.01	0.01
	5	0	0.07	0.03	0.02	0.03
	6	0	0.03	0.15	0.13	0.06
	7	0.11	0.17	0.13	0.09	0.14
	8	0	0.02	0.02	0.02	0.01
	9	0.05	0.07	0.01	0.01	0.04
	10	0.02	0.03	0.01	0.01	0.02
	11	0	0.01	0	0	0

Table E-1. (con't)

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
December	12	0	0.04	0.03	0.03	0.02
	13	0	0.04	0	0	0.01
	15	0	0.02	0	0	0.01
	22	0	0	0.03	0.04	0.01
	23	0.05	0.09	0.07	0.05	0.07
	24	0.03	0.32	0.42	0.47	0.26
	25	0.18	0.33	0.28	0.28	0.26
	26	0.15	0.34	0.20	0.23	0.23
	27	0	0.01	0.02	0.01	0.01
	28	0	0.05	0.08	0.07	0.04
	29	0.02	0.10	0.07	0.06	0.06
	30	0.08	0.07	0.02	0.01	0.06
January (1972)	1	0.01	0.01	0	0	0.01
	2	0.42	0.45	0.30	0.22	0.39
	3	0.26	0.24	0.19	0.10	0.23
	5	0.08	0.08	0.03		0.06
	8	0.03	0.01	0.01	0.06	0.02
	9	0	0.01	0		0
	10	0.08	0.04	0.02		0.05
	11	0.03	0	0	0	0.01
	12	0.50	0.32	0.17	0.15	0.33
	13	0.02	0.02	0.01	0.01	0.02
	17	0	0	0.01	0	0.01
	18	0	0.02	0	0	0.01

Table E-1. (con't).

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
January	21	0.02	0.02	0.01	0.01	0.02
(1972)	22	0.11	0.06	0.03	0.03	0.07
	23	0.37	0.28	0.24	0.16	0.30
	26	0.08	0.06	0.10	0.08	0.08
	27	0.30	0.18	0.11	0.07	0.20
	28	0.06	0.04	0.01	0.03	0.04
	29	0	0.03	0.03	0	0.02
February	1	0.10	0.10	0.05	0.05	0.08
	7	0.01	0.01	0.04	0.02	0.02
	9	0.30	0.35	0.26	0.18	0.30
	10	0	0.01	0	0	0
	13	0.08	0.08	0.07	0.05	0.08
	14	0.45	0.45	0.27	0.23	0.39
	15	0.14	0.14	0.03	0.01	0.10
	16	0.03	0.03	0	0	0.02
	17	0.01	0.01	0	0	0.01
	21	0	0	0.02	0.01	0.01
	22	0.05	0	0	0	0.02
	23	0.03	0.03	0	0	0.02
	24	0.22	0.24	0.10	0.04	0.19
	25	0.11	0.18	0.10	0.04	0.13
	26	0.12	0.04	0.03	0.03	0.06
	27	0.02	0	0	0	0.01
	29	0.06	0.12	0.02	0.02	0.07

Table E-1. (con't).

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
March	1	0.01	0.03	0	0	0.01
	2	0.04	0.18	0.05	0.03	0.09
	3	0.08	0.04	0.02	0.02	0.05
	14	0.20	0.26	0.23	0.16	0.23
	19	0	0.05	0.03	0.03	0.03
	20	0.02	0.10	0.01	0	0.04
	23	0.03	0.09	0.11	0.06	0.08
	24	0	0.01	0	0	0
	26	0.03	0.03	0.05	0.03	0.04
	27	0.06	0.06	0	0	0.04
	28	0.10	0.04	0	0	0.05
	29	0.02	0.02	0	0	0.01
	30	0.12	0.08	0.03	0.03	0.08
	31	0.04	0.05	0.03	0.02	0.04
April	2	0.08	0.10	0.11	0.10	0.10
	3	0.09	0.05	0.02	0.02	0.05
	6	0.03	0.03	0.06	0.07	0.04
	7	----	0.02	----	----	0.01
	10	----	----	0.04	0.05	0.01
	11	0.08	0.38	0.30	0.37	0.25
	12	0.10	0.12	0.17	0.15	0.13
	13	0.45	0.90	0.60	0.45	0.65
	14	0.75	0.78	0.72	0.53	0.75
	19	0.08	0.12	0.08	0.08	0.09

Table E-1. (con't).

Month	Day	Precipitation (inches) at Jankovsky RRG (a)	Foote Creek RRG (b)	Elk Mtn. shielded RRG (c)	Elk Mtn. unshielded RRG (d)	Mean of gages a, b, c
April	21	0.06	0.07	0.09	0.12	0.07
	22	----	0.04	0.05	0.02	0.03
	25	0.07	0.05	0.08	0.06	0.07
	26	1.43	1.08	0.42	0.40	0.98
	27	0.12	0.08	----	----	0.07
	29	0.02	0.04	0.04	0.04	0.03
	30	0.03	0.03	----	----	0.02

Table E-2. Precipitation (inches) at the two non-recording gages, by service period.

Woodedge gage (elev. 8210)		Arlington gage (elev. 7650)	
Service date	Precipitation	Service date	Precipitation
Sept. 21, 1971	Installed	Sept. 28, 1971	Installed
28	0.06	Oct. 15	0.11
Oct. 15	0.18	26	0.24
26	0.13	Nov. 1	0.92
Nov. 1	0.88	9	0.08
9	0.21	18	0.57
18	0.50	26	0.21
26	0.20	Dec. 3	0.27
Dec. 2	0.48	14	0.28
14	0.38	28	1.05
29	1.00	Jan. 3, 1972	0.93
Jan. 3, 1972	0.96	10	0.14
10	0.21	18	0.51
18	0.73	24	0.48
24	0.85	Feb. 1	0.38
Feb. 1	0.59	7	0.13
7	0.08	14	0.74
21	1.40	21	0.23
28	0.82	28	0.63
Mar. 6	0.41	Mar. 6	0.21
21	0.43	21	0.39
Apr. 3	0.82	Apr. 3	0.60
17	2.18	17	1.86
May 1	2.24	May 1	1.50

Table F-1. Water-equivalent storage (ft^3/ft) as measured at all completed fence systems on March 14-16, 1972; adjustment factors for ablation; and estimated values at time of peak accumulation (February 18, 1972).

System Number	Milepost	Water-equiv. behind fences on 3/15	Ablation adjust. factor	Est. peak water-equiv. behind fences	Water-equiv. in cut on 3/15	Ablation adjust. factor	Est. peak water-equiv. in cut	Est. total water-equiv. at peak
1	280.8	593	----	876[a]	0	---	27[a]	903[a]
4	274.9	600	1.36	816	60	1.5	90	906
5A	274.7	651	1.36	885	102	1.5	153	1038
5B	274.5	636	1.36	865	47	1.5	70	935
5C	274.4	536	1.36	729	63	1.5	94	823
6	274.2	769	1.36	1046	27	1.5	40	1086
8	272.1	585	1.36	796	?	?	?	796+
9	271.3	523	1.36	711	67	1.5	100	811
10	270.8	258	1.36	351	64	1.5	96	447
11	270.3	414	1.36	563	70	1.5	105	668
12	269.5	1089	1.36	1481	0	---	0	1481
14C[b]	267.2	292	1.36	397	---	---	---	397
18	263.5	674	1.64	1105	28	1.6	45	1150
19	263.0	778	1.64	1276	111	1.6	178	1454
21	261.8	195	1.64	320	64	1.6	102	422
22	254.2	723	1.64	1186	68	1.6	109	1295
23	253.4	209	----	529[a]	72	---	118[a]	647[a]

[a] Actual values measured at the time of peak accumulation.

[b] Construction of system 14C was not completed until late December (?). Actual storage is therefore significantly less than that which would have accumulated over the entire winter.

Appendix G. Critique of existing fence systems, and recommendations for modifications to maximize performance.

System 1 (milepost 280.8)
Performance satisfactory. No modifications required.

System 4 (milepost 274.9)

Problem : Shirt-tail drift formed at south end of cut. Although it did not encroach on pavement, it could do so during an above-average year.

Cause : Two possibilities. Most important appears to be snow snaking down draw, around ends of fences. Reason is topographic deflection of wind, reinforced around ends of fences. Second possible source is snow moving down draw between systems 4 and 5A, with eddies deflecting snow into cut as it reaches east-bound lane.

Solution:
a. Extend south end of fence 1[a/] by 7 panels (8').
b. Extend south end of fence 2 by 3 panels (8').
c. Extend north end of fence 3 with 6 panels (8').
d. Close gap between 4 and 5A by extending south end of 5A fence 2,430' x 12' and south end of 5A fence 3, 350' x 12'. This recommendation is made more for visibility improvement than for reducing accumulation in cut at Site 4.

System 5A (milepost 274.7)

Problem :
a. Shirt-tail drift in cut, although it probably would never reach shoulder.
b. Erosion of drift behind lead fence causes some prolonged drifting across road near cut 5B. Could have adverse effect on road ice formation when rest of road is bare.

Cause : Lead fence (#1) was located on a long ridge oblique to prevailing wind. This made fence extremely efficient, but the tail of the drift tends to erode under strong southwest winds.

Solution: Extend north end of fence 2, 260', with alignment parallel with centerline (H = 12').

[a/] Fences are numbered with 1 as the lead (farthest upwind) fence.

Appendix G. Continued

System 5B (milepost 274.5)

Problem : None, but would be wise to extend fence #2 (north end) so as to maximize visibility improvement between Systems 5B and 5C. Length = 100' .

Gap between 5C and 6 (milepost 274.3)

Problem : None with sites 5C or 6, present systems o.k. However, gap between systems may present driving hazard (visibility or ice).

Solution: To close gap.

a. Extend fence 2, system 6, 600 ft to south, in line with existing fence (H = 12').
b. Extend north end of fence 1, system 5C, 250'+ (as far as range fence will permit). H = 8'.
c. Construct new 8' fence to close gap between fence 3 (Site 6) and fence 2 (Site 5C), but offset downwind to avoid range fence.

System 8 (milepost 272.1)

Problem : A bust -- still getting significant snow accumulation at interchange structure.

Cause : Wind direction nearly parallel to highway. Significant snow movement down corridor between present system and road, due to County road location. Most of snow, however, is moving down median.

Solution:

a. Erect fences in median using "parabolic" design. Maximum height of fences should be 1.0 ft below shoulder elevation. Five fences at 160' spacing.
b. Extend existing fence 4, 100' on north end, using 8' fence.
c. Extend fence 2, 3 panels on north end (H = 12').
d. Erect new 8' fence 225' long, between existing fences 2 and 3. North end to be butted up to range fence.

System 9 (milepost 271.3)

Problem : System performs satisfactorily, but may run out of capacity in an average year.

Solution: None recommended at this time.

System 10 (milepost 270.8)

Problem : None. Satisfactory.

System 11 (milepost 270.3)

Problem : None. Satisfactory.

System 12 (milepost 269.5)

Problem : None. System performs perfectly. Present design is adequate for the average year only.

Solution: Storage capacity could be increased easily by adding an additional 600' of 8' fence to connect existing fences 1-south and 1-north.

System 14C (milepost 267.2)

Problem : Some snow still accumulating under WBL structure (County Road separation), but mainly on east side.

Cause : a. Snow source on R/W, mainly in gore.
b. Snow deflected down County Road.

Solution: Problem not too serious. Not much can be done because of layout. Suggest extending south end of fence #2, 100' (H = 12').

If problem is severe enough in future years, might try using low (4') fences in the gore area.

System 18 (milepost 263.5)

Problem . System was about 85% full in 1971-72 winter. May run short of capacity in any above-average year.

Solution: If problem appears in future years, add one 8' fence upwind. Northing recommended at this time.

System 19 (milepost 263.0)

Problem : System was about 85% full in 1971-72 winter. May run short of storage in an above-average year.

Solution: Add single 8' fence between existing fences, if problem warrants in future years.

System 21 (milepost 261.8)

Problem : None. Satisfactory.

System 22 (milepost 254.2)

Problem : Good performance, but shirt-tail drift near south end of cut. Doesn't appear to offer significant threat, but minor modifications could reduce it.

Cause : a. Gap between fences 2 and 3 -- insufficient overlap.

b. Source area between R/W and fence #s 3 and 4, and 4 and 5.

Solution: a. Extend fence 3, 4 panels to north (H = 8').

b. Extend fence 4, 7 panels to north (H = 8').

System 23 (milepost 253.4)

Problem : Appreciable accumulation in center of cut. Although it reached 6 ft in depth at greatest accumulation, it never posed a threat to roadway -- might in an average year, however.

Cause : Uncertain, but source is probably between R/W and fence 3, since this distance exceeds 300 ft.

Solution: Construct new 8' fence 230' downwind of fence 3. Terminate north end where it becomes spaced at 100 ft from R/W fence.